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An investigation of inspections by remotely operated vehicles in the offshore oil and gas structures

São Paulo
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RESUMO

DALHATU, A. A. **Estudo e análise de inspeções por veículos operados remotamente nas estruturas offshore de óleo e gás**. 2023. Dissertação (Mestrado) – Escola Politécnica, Departamento de Engenharia de Minas e de Petróleo, Universidade de São Paulo, São Paulo, 2023.

A presente dissertação fornece uma visão geral e perspectivas das inspeções de ROV na indústria de óleo e gás e discute possibilidades futuras para o avanço contínuo do campo. O objetivo desta dissertação foi identificar os métodos e técnicas de condução de operações de inspeção baseadas em ROV e identificar o método mais eficiente de condução de inspeções com ROV. Isso foi alcançado por meio de uma revisão integrada da literatura. Há pouca ou nenhuma informação coerente na literatura sobre as novas tecnologias que surgem como métodos alternativos para realizar operações de inspeção e intervenção menos dispendiosas e mais eficientes, e como elas estão atualmente ultrapassando as classificações conhecidas de ROVs. Nesse sentido, constatamos que urge a necessidade de haver mais investigações nessa área para fornecer informações coerentes. Isso ajudará a entender melhor os ROVs e sua aplicação de uma perspectiva geral e contribuirá na classifição dos ROVs para atender aos desenvolvimentos modernos. Alem disso, identificou-se, entre os métodos emergentes de inspeção manutenção e reparos, que a tecnologia Drone ROV, juntamente com o método Resident ROV, são os métodos mais confiável e eficiente de conduzir operações de ROV.

Palavras-Chave – ROV, IMR, Óleo e Gás, Métodos de inspeção, Técnicas de inspeção.

ABSTRACT

DALHATU, A. A. **An investigation of inspections by remotely operated vehicles in offshore oil and gas structures**. 2023. Dissertação (Mestrado) – Escola Politécnica, Departamento de Engenharia de Minas e de Petróleo, Universidade de São Paulo, São Paulo, 2023.

This investigation provides an overview and outlook of the ROV inspections in the oil and gas industry and discusses future possibilities for the continued advancement of the field. The specific problem for this dissertation is to identify the methods and techniques of conducting ROV-based inspection operations and to identify the most efficient method of conducting ROV inspections. This was achieved through an integrative literature review methodology. There is little to no coherent information in the literature about the new technologies emerging as alternative methods for conducting less costly and more efficient inspection and intervention operations, and how they are currently out-dating the known classifications of ROVs. Further investigation is needed to provide coherent information. This will help to better the understanding of ROVs and their application from an overview perspective and help to better classify ROVs to fit modern developments. This research provided a new classification of ROVs that fits modern developments and has identified, among the emerging methods of IMR, that the Drone ROV technology along with the Resident ROV method is the most reliable and most efficient method of conducting ROV operations.

Keywords – ROV, IMR, Oil & Gas, Inspection methods, Inspection techniques.

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LIST OF ACRONYMS

AET - Acoustic Emission Testing

ACFM - Alternating Current Field Measurement

AR - Augmented Reality

AROV - Autonomous Remotely Operated Vehicle

AUV - Autonomous Underwater Vehicle

ASV - Autonomous Surface Vehicle

BP - British Petroleum

CT - Computed Tomography

CVI - Close Visual Inspection

CUI - Corrosion Under Insulation

CTL - Coplanar Translational Laminography

DDA - Digital Detector Arrays

DROV - Drone Remotely Operated Vehicle

DR - Digital Radiography

DVL - Doppler Velocity Log

DVI - Detailed Visual Inspection

ECT - Eddy Current Testing

FPU - Floating Production Unit

FSV - Field Support Vessel

FROV - Fast Remotely Operated Vehicle

GVI - General Visual Inspection

GPS - Global Positioning System

HAZID - Hazard Identification

HAZOP - Hazard Operation

HROV - Hybrid Remotely Operated Vehicle

ICAO - International Civil Aviation Organization

ICROV - Inspection Class Remotely Operated Vehicle

IMCA - International Marine Contractors Association

IMR - Inspections, Maintenance, and Repairs

INS - Inertial Navigation System
LARS - Launch and Recovery System
LED - Light-Emitting Diode
LIDAR - Light Detection and Ranging
MAS - Maritime Autonomous Systems
MASS - Maritime Autonomous Surface Ship
MEC - Magnetic Eddy Current
MODU - Mobile Offshore Drilling Unit
MPI - Magnetic Particle Inspection
MSROV - Medium Size Remotely Operated Vehicle
NDT - Non-Destructive Testing
OCROV - Observation Class Remotely Operated Vehicle
ORS - Object Recovery System
OTC - Offshore Technology Conference
PEC - Pulse Eddy Current
PECT - Pulse Eddy Current Testing
RF - Radio Frequency
RIS - Riser Inspection System
ROV - Remotely Operated Vehicle
RPV - Remotely Piloted Vehicle
RT - Radiographic Testing
RROV - Resident Remotely Operated Vehicle
SA - Situation Awareness
SDS - Subsea Docking Station
SPS - Subsea Production System
S-RROV - Semi-Resident Remotely Operated Vehicle
TMS - Tether Management System
TOFD - Time-of-Flight Diffraction
UAS - Unmanned Aircraft System
USP - Unmanned Support Platform
USV - Unmanned Surface Vehicle
UT - Ultrasonic Testing

UUV - Unmanned Underwater Vehicle

VT - Visual Testing

WCROV - Work Class Remotely Operated Vehicle

WHOI - Woods Hole Oceanographic Institution

CONTENTS

1 INTRODUCTION

1.1 Research Background

Offshore oil and gas structures include several installations such as platforms, floating facilities, subsea equipment, pipelines, cables and spools or jumpers, and auxiliary installations. Offshore water is saline and the offshore oil and gas structures remain underwater subjected to a variable load due to sea tides. Hence, Inspections, Maintenance and Repairs (IMR) are carried out frequently. IMR is a term used for subsea inspection and intervention (Maintenance and Repairs) operations and its objective is to facilitate safe and cost-efficient “inspection and intervention” on subsea installations, to maintain a sustainable operation of offshore assets. The main focus of this dissertation is the inspection part of IMR operations within the oil and gas industry.

IMR used to be performed with human divers and manned subs, today they are performed with the help of Remotely Operated Vehicles (ROV)s that replaced human divers and manned subs in the ’70s (XIANG et al., 2015). The IMR industry (Subsea Operators) performs operations by hiring a specialized vessel with the crew from the vessel owner or the shipping company which may have several people on board belonging to several companies, plunging the operations into hundreds of thousands of dollars and especially more sophisticated ROV inspections are not excluded from this process. For complex intervention operations, this is understandable but with current developments in ROV technology, it is certainly not necessary for most inspection tasks and basic manipulation. Visual inspections of offshore assets, like pipelines or subsea structures, can be efficiently performed using ROVs equipped with high-definition cameras. These inspections focus on capturing visual data and don’t require complex equipment or extensive intervention. Hence, specialized vessels and crews are unnecessary as ROVs can operate from smaller support vessels or directly from the shore. Similarly, basic manipulation tasks such as valve turning, sample collection, or equipment deployment can be completed using ROVs with manipulator arms and specialized tools. These tasks don’t demand the resources and crew needed for complex interventions, allowing ROVs to be remotely operated by skilled technicians from onshore control centers or smaller support vessels, eliminating the need for a fully equipped IMR vessel.

The other aspect concerning ROV-based inspections is the techniques used to inspect offshore assets. The ROV utilises add-on tools and ancillary sensor instrumentation to achieve this. The basic technique of ROV-based inspection is the camera, by visual inspection. More advanced ROV-based inspections are carried out by the use of Non-Destructive Testing techniques (NDT).

This dissertation investigates and reviews ROVs and the methods and techniques of conducting ROV inspection operations in the oil and gas industry by building information in an organized and resourceful manner to provide a meaningful understanding.

The goal of this research is to investigate, present and describe the current state and future of ROV-based inspections in the oil and gas industry. This research offers a contribution to the IMR industry, by finding out and grouping the emerging methods of conducting IMR operations, discerning how they are shaping ROV classification and presenting a classification or taxonomy that better stratifies ROVs, that fits modern developments. The aim is to have a thorough look at the existing research and attempt to draw out conclusions about the future of the inspections in IMR industry.

1.2 Problem statement

Subsea inspection and intervention operations are cumbersome, expensive and difficult to execute due to the support vessel and its accompanying logistics (SCHJØLBERG et al., 2016; JOHANNESSEN; MCARTHUR; JONASSEN, 2015). It is one of the major challenges being faced in the industry. Whilst the existence of ROVs had helped to eliminate risking human lives, the current offshore inspection and intervention operations have posed yet another challenge, high cost. The challenge of this cost still remains but new technologies are emerging to mitigate the problem (ANDERSON, April 30 2018).

These new technologies are emerging to be new methods of conducting inspection and intervention operations which consequently disrupt and blur the previously accepted lines of demarcation differentiating ROVs, which already lack a widely accepted standardized ROV classification (JAKUS; OLEJNIK, 2017). The ROV classification was defined by grouping ROV functions and capabilities needed for generalised scenarios. The classification also placed too much attention on the mode of communication (tether & wireless) and operation (teleoperation & level of 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. In line with current modern developments and from observation of the actual practice, there is a need for a sustainable taxonomy for ROVs.

There is little to no coherent information in the literature about the new technologies emerging as alternative methods for conducting less costly and more efficient inspection and intervention operations, and how they are currently out-dating the known classifications of ROVs. Further investigation is needed to provide coherent information, this will help to better the understanding of ROVs and their application from an overview perspective and help to better classify ROVs to fit modern developments.

1.3 Research questions

The purpose of the research is to investigate ROV-based inspections in the offshore oil and gas industry by researching new publications on ROVs and IMR. The research aims to answer the following questions:

1. what are the methods of conducting inspection operations and how do the new technologies affect ROV classification?
2. what are the techniques utilised in the inspection of offshore assets?
3. what is the most efficient method of conducting inspections and what is the future of offshore asset inspection?

1.4 Research Motivation

The motivation behind this research stems from the challenges and opportunities in the field of ROV-based inspections in the offshore oil and gas industry. While ROVs have significantly improved the safety and efficiency of subsea inspection and intervention operations, there are still limitations and inefficiencies that need to be addressed.

Firstly, the current practice of relying on specialized vessels and crews for ROV inspections is often expensive and unnecessary for routine inspection tasks and basic manipulations. With advancements in ROV technology, it has become evident that smaller support vessels or even onshore control centers can effectively carry out these tasks. By exploring alternative methods and highlighting the cost-saving potential of such approaches, this research aims to drive more sustainable and cost-efficient practices in the industry.

Secondly, the existing classification system for ROVs lacks standardization and fails to account for the emerging technologies and methods that are reshaping the industry. This hinders the clear categorization and understanding of different types of ROVs, limiting their effective utilization. By investigating the impact of new technologies on ROV classification and proposing a more comprehensive and adaptable taxonomy, this research aims to provide industry stakeholders with a better understanding of the capabilities and limitations of different ROV types.

Furthermore, there is a lack of coherent information in the literature regarding the emerging technologies and their implications for ROV-based inspections. This research seeks to bridge this gap by systematically reviewing and analyzing relevant publications, consolidating knowledge, and providing a comprehensive overview of the current state and future directions of ROV inspections in the offshore industry.

The motivation behind this research is to contribute to the IMR industry by advancing the understanding of ROV-based inspections, identifying cost-effective and efficient methods, and proposing a sustainable taxonomy that aligns with the modern developments in the field. By addressing these research objectives, this study aims to support informed decision-making, improve operational efficiency, and enhance the overall performance of inspection and intervention operations in the offshore oil and gas industry.

1.5 ROV Market in the Oil and Gas Industry

The Remotely Operated Vehicle (ROV) market has emerged as a crucial component within the oil and gas industry, revolutionizing offshore operations and enabling efficient subsea inspections, maintenance, and intervention tasks. ROVs are remotely controlled underwater robots equipped with advanced sensors, cameras, and manipulator arms, allowing operators to carry out intricate tasks in challenging underwater environments.

The ROV market has witnessed significant growth in recent years an will continue to grow [1], driven by the increasing demand for offshore exploration and production activities. The market is characterized by a diverse range of players, including major manufacturers, service providers, and technology developers. These industry participants continually strive to enhance ROV capabilities by incorporating cutting-edge technologies such as

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[1] https://www.mordorintelligence.com/industry-reports/rov-market

automation, artificial intelligence, and augmented reality.

Technological advancements in ROV systems have expanded their applications beyond traditional inspection tasks. ROVs are now utilized in a wide range of activities, including subsea construction, pipeline installation and maintenance, underwater surveys, and environmental monitoring. The versatility and adaptability of ROVs make them indispensable tools in ensuring the safety, reliability, and sustainability of offshore assets.

Despite the positive growth trajectory, the ROV market also faces challenges. These include the need for continuous innovation to meet evolving industry demands, addressing concerns related to cost-effectiveness, ensuring regulatory compliance, and optimizing operational efficiency. Understanding market trends, competitive dynamics, and emerging opportunities is crucial for stakeholders to make informed decisions and stay ahead in this rapidly evolving sector.

The ROV market in the oil and gas industry is experiencing substantial growth and evolving with technological advancements [2]. The market offers significant opportunities for companies involved in the development, manufacturing, and operation of ROV systems. This dissertation aims to provide a comprehensive analysis of the ROV market, exploring its current landscape, trends, growth drivers, and future prospects within the context of offshore inspections on structures.

1.6 Methodology

An integrative review was utilised as the research method. Utilising this method will enable the emergence of a new perspective on the topic of ROVs. The aim of an integrative review is “to assess, critique, and synthesise the literature on a research topic in a way that enables new perspectives to emerge” (SNYDER, 2019).

The questions of the research and its process were developed. To limit and focus the direction of the research, an experimental search was conducted to find out the relevant keywords and digital libraries to be used in the study. A search strategy was then defined and relevant data to be extracted were noted.

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[2] https://www.fortunebusinessinsights.com/industry-reports/offshore-auv-rov-market-100432

1.6.1 Search strategy and databases

“Google Scholar is a very powerful open-access database that archives journal articles as well as “grey literature”, and Rowland (2008) compared Google Scholar to other open-access search engines. They found that Google Scholar performed the best (XIAO; WATSON, 2019). For this reason, pilot queries were carried out in March 2019 using exclusively google scholar, Keywords like “Remotely Operated Vehicles”, “offshore”, “oil and gas”, “ROV”, “Inspections” and “IMR” were used in the pilot queries. The research questions were used as a base to form the final search query and the results were limited to research papers that included inspections in the oil and gas industry. The popular synonyms IRM for IMR were linked to the query using OR.

This study was done using scientific publications. Other sources of information regarding ROVs and IMR were books and major ROV company sites. Finally, several methods and techniques of inspections have been investigated and compared. A detailed description of their pros and cons has been discussed. It should be kept in mind that the literature review process can be iterative, and unforeseeable issues might arise that might necessitate modifications to the research questions and review protocol.

1.6.2 Conducting the study

The papers used in this review ranged mostly from 2015 to 2021. The search was finalised on the 15th of April 2021. This is important because of new scholarly works that might have been published afterwards.

1.7 Structure of the dissertation

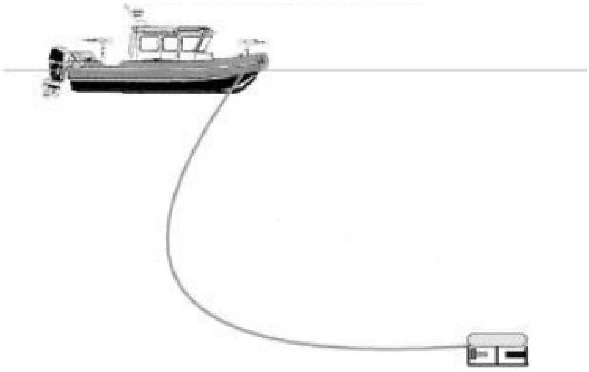
1. Chapter 1 Introduction
2. Chapter 2 Characterization of ROVs
3. Chapter 3 Characterization of ROV Subsystems
4. Chapter 4 ROV application in offshore
5. Chapter 5 Analysis of Trends and Emerging Technologies
6. Chapter 6 Conclusion.

2 CHARACTERIZATION OF ROVS

This chapter explores various aspects related to the characterization of ROVs. By understanding the fundamental characteristics of ROVs, we can gain insights into their capabilities, limitations, and potential applications. This chapter sets the foundation for a deeper exploration of ROVs and their role in enhancing the efficiency, safety, and effectiveness of offshore operations.

Traditionally, ROVs are connected to a surface vehicle via a tether, see Figure 1. They range in complexity and come in many different sizes and capabilities (BOGUE, 2015). They are equipped with cameras and lights and many other add-ons and instrumentation depending on what is required. Today, ROVs have advanced, they can operate autonomously and be remotely piloted from onshore through communication carried by satellite or 4G networks (NEWELL, 2018).

Figure 1: Basic ROV setup



Source: Christ and Sr (2013)

ROVs operate in various modes, including remote control mode, where they are piloted by operators in real-time, and autonomous mode, where they execute pre-programmed tasks independently. Autonomous Underwater Vehicles (AUVs) represent a specialized class of ROVs that operate primarily in autonomous mode, performing tasks such as underwater mapping, scientific data collection, and environmental monitoring. Hybrid ROVs (HROVs) combine the capabilities of ROVs and AUVs, enabling them to transition between autonomous and remotely piloted modes, depending on the mission requirements.

ROVs are classified based on their size, capabilities, and intended applications. This classification helps in categorizing ROVs into different classes and types, allowing for better understanding and standardization within the industry.

These various aspects of this chaspter, including ROV modes of operation, AUVs, HROVs, and ROV classification, collectively contribute to the characterization of ROVs. Understanding these features provides a comprehensive view of ROVs. The following sections explores in more detail the ROV characterization.

2.1 ROV modes of operation

There are three modes in which ROVs can be operated: teleoperation, semi-autonomous and fully autonomous or simply autonomous. ROVs are controlled from onboard controls rooms on the support vessel or from control stations onshore, depending upon the size and capacity of the ROV, the control station can be a simple joystick control and a video display, a large container or even a large remote control rooms (CHRIST; SR, 2013). Most communications with ROVs have been via tethers thus far. All efforts made to implement high-frequency wireless communication in water have proven futile and hence the means of the physical communication medium has been the only choice currently. However, the forms of communication may come as hard-wire communication, acoustic communication, optical communication or Radio Frequency (RF) communication, depending upon the distance and medium through which the communication must take place (CHRIST; SR, 2013). The following sections provide a background of ROV operation modes.

2.1.1 Teleoperation (Human Operated)

Teleoperation is performed when the operator is in full control of the vehicle, guiding it through received camera footage. It can be defined as extending one's abilities to a remote environment. The cooperation of humans and robots achieves this as they both excel at different abilities. Teleoperation is a system where the human interacts with the robot to complete a task that neither of them could perform alone. It is made up of a master device, a slave device and a controller. The master device is controlled by the human to give inputs to the slave device. The connection between the slave device and the master device is the controller (TZAFESTAS, 2012).

2.1.2 Autonomous

In this mode, the vehicle can locate its position on a map and generate its trajectory to the assigned waypoints. The system receives prior knowledge of environmental information including the candidate sequence of waypoints. The vehicle is capable of independent operation as it is advanced with a high-level Situation Awareness (SA), real-time path planning, the ability of contingency management, and task scheduling. Autonomy has several levels which were defined by classes or taxonomies and grouping functions needed for generalised scenarios, for example, Sheridan and Verplank (1978) introduced a scaled metric known as Sheridan's scale with 10 levels of autonomy, Yazdani et al. (2017) introduced a new classification/taxonomy in which contains 9 levels of autonomy, and Veres et al. (2011) considered a simple 3 level of autonomy, this is the generally known autonomy level, which we discussed thus far as the three modes of operation. However, this suggests discrete levels of autonomy in the whole mission, and it is misleading to refer to the system as completely autonomous, from observations of actual practice and cognitive science perspective (ZADEH; POWERS; ZADEH, 2020). This problem has extended to the classification of Unmanned Underwater Vehicles (UUV) as a whole causing serious ambiguities. Autonomy and the absence of a tether are the main elements used to differentiate ROVs and AUVs. In the following sections, we will discuss AUVs, and Hybrid ROVs and demonstrate how differentiating AUVs from ROVs in this rapidly advancing technology is inconsequential.

2.1.3 Semi-autonomous

Semi-autonomous is a mixture of autonomy and human interaction. The vehicle is advanced with Situation Awareness (SA) and the capability of path planning. It operates under the supervision of an operator who can intervene to take control of the vehicle when it is unable to perform the assigned task. In a simple scenario, the navigation system of the underwater vehicle indicates the intermediate waypoints, it has the capability to avoid collisions, depart and return autonomously, and plan the paths between waypoints. However, the operator does the mission re-planing (ZADEH; POWERS; ZADEH, 2020). The operator performs mission replanning by actively monitoring the ROV's progress and making adjustments to the mission parameters as needed.

2.2 Autonomous Underwater Vehicles

AUVs are part of the group of Unmanned Underwater Vehicles (UUVs) along with ROVs. They are considered to be an independent group because of their autonomous capability and absence of a tether. But in reality, AUVs are not completely self-governing. This certainly presents a bit of ambiguity on whether they are ROVs operated with some autonomous capabilities or an independent class called AUVs with partial autonomy. Another complication is the misapprehension of the terms **automatic** and **autonomous**. Autonomous operations and automatic operations are considerably different. Autonomous operations are free of any human intervention as the system has the capability of recognising the circumstances to plan or re-plan to execute the mission under new circumstances, it constantly adapts to a continuously changing environment without human involvement. While automatic operations, the system only executes programmed commands without any capability of making decisions to operate under new circumstances, without the capability of placing its actions in the context of its environment. The autonomous platforms we have today still rely on human interventions to handle complex operations. For a vehicle to be genuinely autonomous, there is a need for more situation awareness, which is a level of consciousness of having the ability to sense, detect, comprehend and operate in environmental circumstances (ZADEH; POWERS; ZADEH, 2020).

For these reasons current AUVs are not really self-governing or truly autonomous but can be seen as a variant of the ROV with some level of autonomy, however, enhancing the SA level of Unmanned Vehicles (UV) can advance their capacities from full human control to completely self-governing (autonomous) control. When it comes to tethering as a criterion for distinguishing, with technological improvements in underwater communication the presence or absence of a tether will no longer matter as a distinguishing criterion. Consequently, there is an emergence of new vehicles termed Hybrid ROVs that might finally put an end to the dilemma.

2.3 Hybrid ROV

HROVs are ROVs that have the capabilities of AUVs, they completely blur the difference between AUVs and ROVs. Operations have already been carried out using this vehicle type in both ROV and AUV modes, albeit, using support vessels of opportunities (GRASSO et al., 2016). They emerged as a result of the emerging methods of IMR execution driven by the high cost and daunting process of the traditional method (JO-

HANSSON; SIESJÖ; FURUHOLMEN, 2011; CHARDARD; COPROS, 2002), these shall be discussed in chapter three. The idea began with the SWIMMER concept, a hybrid ROV which was proven in 2001, it became technically mature for industrialization in 2006 (GRENON; FIDANI; TSOUZA, 2006). The SWIMMER was attached to an AUV in the same body to transport it to the site and attach it to the Subsea Docking Station (SDS). The hybrids of today, like their predecessor, have an SDS situated near the Subsea Production System (SPS). The SDS is installed on the seafloor at the site, it is where the ROV receives its power, communication and shelter. SDS is built to serve a unique vehicle but recently universal SDS has begun to emerge (MASLIN, 2020; BOGUE, 2019). Over the past years, there have been several projects on HROVs; in 2015, Aquabotix released the hybrid Autonomous Remote Vehicle (ARV), a hybrid vehicle that can operate as an AUV or ROV for the purpose of the survey and inspection (WHITFIELD, 2017). Woods Hole Oceanographic Institute (WHOI), also developed an ROV called Nereus which can function as an autonomous vehicle (YUH; MARANI; BLIDBERG, 2011).

The difference between ROVs and AUVs is minor and this minor gap is rapidly closing. 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. Currently, it is not important whether a vessel is called ROV, AROV or AUV. What matters is that they are subsea vehicles (with different modes of operation) (WHITFIELD, 2017). HROVs can operate in all three modes of operation, they can have a “person in the loop” that operates from another location giving the opportunity of more robust operational integrity (VINCENT; SEVINC; HERBST, 2019), in a semi-autonomous mode. Saab underwater systems[1] also have the concepts of operation and design of an HROV offshore system that can be operated in these modes. The vehicle transits to the location in an autonomous mode and can perform pre-programmed inspection and survey tasks along with other tasks performed manually through the use of tether or low-frequency acoustics (JOHANSSON; SIESJÖ; FURUHOLMEN, 2011). Clean sea HROV developed by Eni and Tecnomaye also operates both in AUV (automatic) and ROV (manual) mode without the need for TMS, and a lightship could be used to transport it to the site, resulting in significant cost reduction (GRASSO et al., 2016). HROVs can also be in the form of a micro ROV, such as that developed by Vincent, Sevinc and Herbst (2019). A foundation on AUVs and HROVs is a prerequisite to better understanding the classification of UUVs and building upon the current classification of ROVs.

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

2.4 ROV Classification

It is still problematic to classify ROVs and UUVs in general even for 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 (2017) there are mainly four identifiable approaches or schools of thought to ROV and/or UUV taxonomy, the four approaches are as follows:

1. ROVs should not be classified
2. ROVs should be classified but needs frequent update
3. ROVs should be classified based on weight
4. ROVs should be classified based on the purpose

ROVs 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, and perhaps a vehicle that doesn't fit into the existing classification system. Hence it is pointless to try and classify the vehicles.

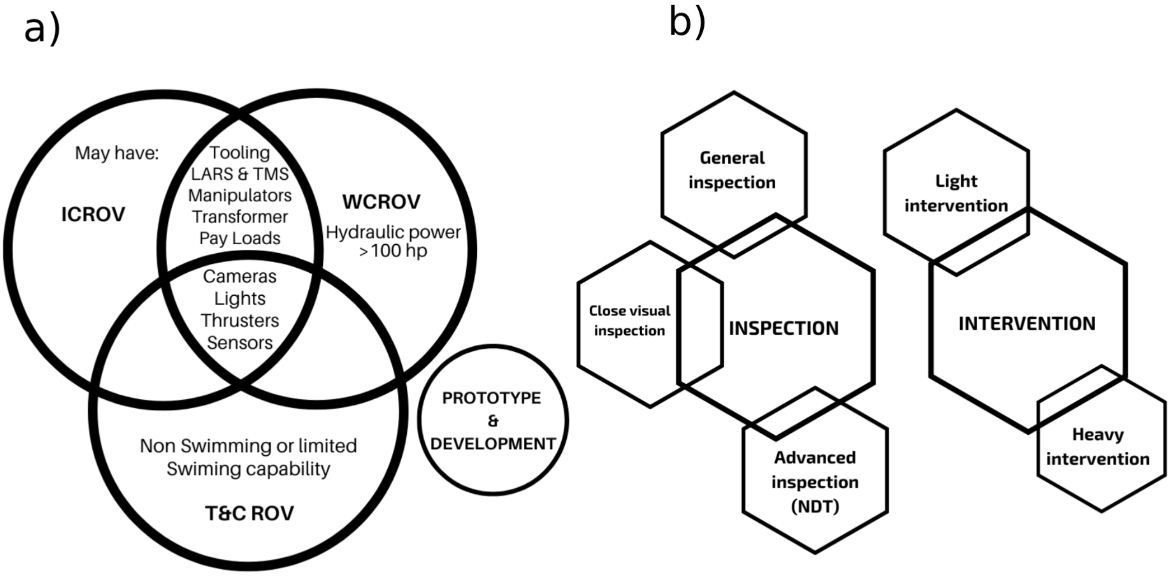
ROVs should be classified but needs frequent update: This approach holds the belief that ROVs the classification can be renewed every time the classification goes out of date, this school of thought believes that this enhances the ROV taxonomy.

ROVs should be classified based on weight: This approach proposes that vehicles can be classified based on a single criterion, weight.

ROVs should be classified based on purpose: This fourth approach is mainly purpose-based. It is quite an open approach that allows flexibility in classifying the vehicles in terms of their objectives and the potential interests of the classifier. In the case of manufacturers, on their websites, one can find the classification of vehicles based on mass and the power of the thrusters.

The International Marine Contractors Association (IMCA), which is one of the main organisations and associations issuing norms and standards in the oil and gas industry, also follows this approach for classification.

Figure 2: (a) Shared and non-shared ROV components and (b) IMR operations capabilities that determine the classification



Source: Dalhatu et al. (2023)

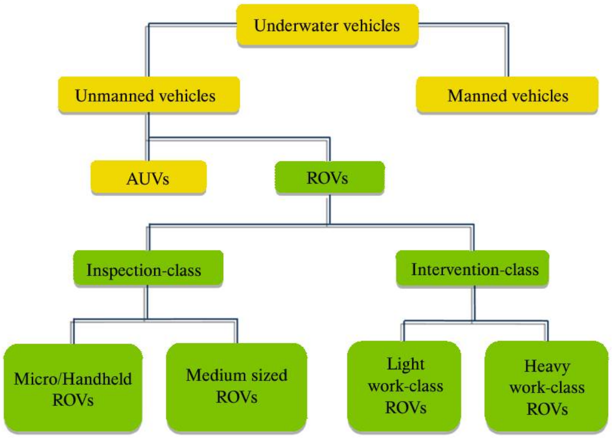
The fourth approach utilises the various ROV tasks to classify the vehicles (See Fig 2(b)). For example, it can be seen from the classification given by Capocci et al. (2017) in Fig. 3 that he provided a basic classification based on the ROV tasks in Fig. 2(b). The approach does not provide a reliable classification because the lines of demarcations between vehicle classes evolved as ROV technology matured, starting with the driving force of the prime mover, which is either hydraulic or electric based (CHRIST; SR, 2013). But today, they are also classified based on weight, depth rating and horsepower as shown in figure 4(a). They are also classified based on 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 figure 2(b).

Here, we will examine the old IMCA classification, the classification by Capocci et al. (2017) and the classification by Christ and Sr (2013), then we will condense upon 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 and they have earlier classified ROVs into 6 groups:

1. Class I - Observation ROVs

Figure 3: Underwater Vehicle Outline



Source: Capocci et al. (2017)

2. Class II - Observation ROVs with Payload Option
3. Class III - Work-class ROV
4. Class IV - Towed and crawling (T& C) vehicles
5. Class V - Prototype and development

The list was updated by IMCA in 2016 [2]. It is an expanded list of the old one, based on the increased diversification of tasks performed. This new code includes an expanded form of ROV classification, 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.
3. Class IIB – Observation class vehicles with light intervention/survey and construction capability.
4. Class IIIA – Standard work class vehicles with a payload of less than 200kg and through frame lift of approx. 1000kg.
5. Class IIIB – Advanced work class vehicles with a payload of greater than 200kg and through frame lift of up to 3000kg.
6. Class IVA – Towed vehicles, typically ploughs used in subsea cable burial operations.

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

7. Class IVB – Tracked vehicles utilising HP water jetting and specialised rock-cutting tools, again used in the burial of subsea cables and pipelines.
8. Class V – Prototype or development vehicles.
9. Class VIA – Autonomous Underwater Vehicles (AUV) weighing less than 100kg.
10. Class VIB – Autonomous Underwater Vehicles weighing greater than 100kg.

The new IMCA classification is an expansion of the old IMCA classification, since our aim is to integrate, we will make use of the old classification. Based on the old IMCA classification, Observation Class ROVs (OCROV) Class I and OCROV Class II have the same fundamental function of observation, 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 it being Class I or Class II. Hence, the option of the payload is a subcategory which fits into the subcategory of the Inspection Class ROV (ICROV) subcategories mentioned by Capocci et al. (2017) and the observation class mentioned by Christ and Sr (2013).

Therefore we provide a class named ICROV with two subcategories as shown in Fig. 4(b). The weight demarcation parameter is a strong constant regardless of the progress of technology and increased capability. But the performance and depth capability criteria are weak because technology is rapidly catching up with the larger vehicles.

For this reason, Medium Size ROVs (MSROV)s classification is not grounded. Because large MSROVs are categorised as vehicles that have a weight greater than 32kg, the shallow and deepwater MSROVs can be categorised as large ICROVs with payload, higher depth and more operational capabilities.

The heavy MSROV as categorised by Christ and Sr (2013) utilises both electric and hydraulic power, which is why it is often called a light WCROV. According to Christ and Sr (2013) 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. 4(b).

All ROVs have common components such as lights, cameras, thrusters and other necessary electronics as shown in Fig. 2, but they can be differentiated by the uncommon components. For example, WCROVs use hydraulic power to drive moving components, either fully or partly and have greater than 100hp. On the hand, some components may or may not be used in ICROVs, as shown in Fig. 2(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 Testings (NDT) techniques to inspect the health of subsea offshore assets. Since WCROVs can be equipped with a unique system for Riser Inspection (RIS). This means some inspections have to utilise a vehicle that falls into the WCROV class to perform certain inspections because light intervention tasks are also part of inspections and the ROVs are equipped with manipulators and cleaning tools, dedicated tools such as torque tools for manual valves operation and override remotely actuated valves, connect & disconnect electrical flying leads, development and management of seabed nodes, cleaning & jetting etc. This means that the classifications based on capabilities and purpose are a bit misleading as there are compromises.

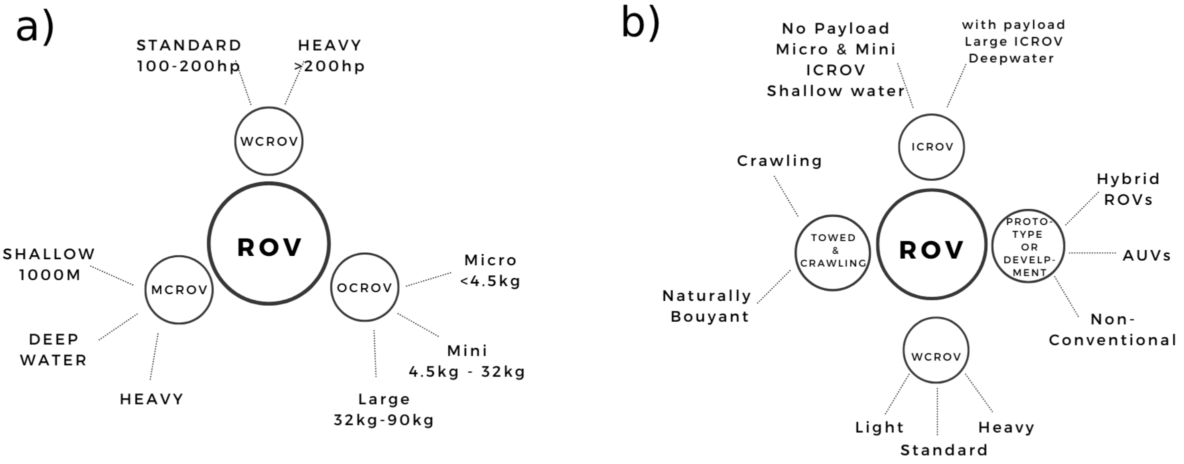
Aside from basic camera visual inspection, inspection class vehicles can carry out small tooling operations such as cleaning, latching or recovering the item using manipulators and auxiliary equipment. Any class of ROV can be utilised for the purpose of inspection, therefore classifying ROVs based on their purpose can be considered misleading as there are compromises. Some inspections have to utilise a vehicle that falls into the WCROV to perform certain inspections.

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

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

In many ways Unmanned Underwater vehicles (UUVs) and Unmanned Aircraft Systems (UAS) are alike. For example, in aviation, UAS is classified as a remotely piloted or autonomous system by many. However, the same question of remote operation, true autonomy and autonomy levels still exist (EL-SAYED, 2016). One might ask if these

Figure 4: Classification of ROVs based on the fourth approach



Source: Dalhatu et al. (2023)

vehicles are truly different vehicles 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 (2016) stated

> Remotely Piloted Vehicle (RPV), or Unmanned Aircraft System (UAS) is an aircraft that flies without a human crew on board the aircraft. There are a wide variety of UAS shapes, sizes, configurations, and characteristics. UAS 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, 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” (CLOTHIER; WILLIAMS; PEREZ, 2014). 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 arises, the basic definition of remote operation or teleoperation indicates the operation of a system or machine at a distance. By eliminating the human element, technically, all UUVs and UASs are remotely operated systems, from another perspective while autonomous machines, underwater and air are considered to be autonomous, they at the same time in many aspects are teleoperated. For example, in the automotive industry, most leading companies believe that teleoperation capability is a necessity in bridging the gap between self-driving cars and the adoption of autonomous vehicles, meaning, the teleoperation of autonomous vehicles. Tele-operation 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 in place, it becomes clear that autonomy and remote operation are modes of operation, hence, HROVs and AUVs can be clearly seen as belonging to the same grouping albeit belonging to different branches in a well-defined taxonomy.

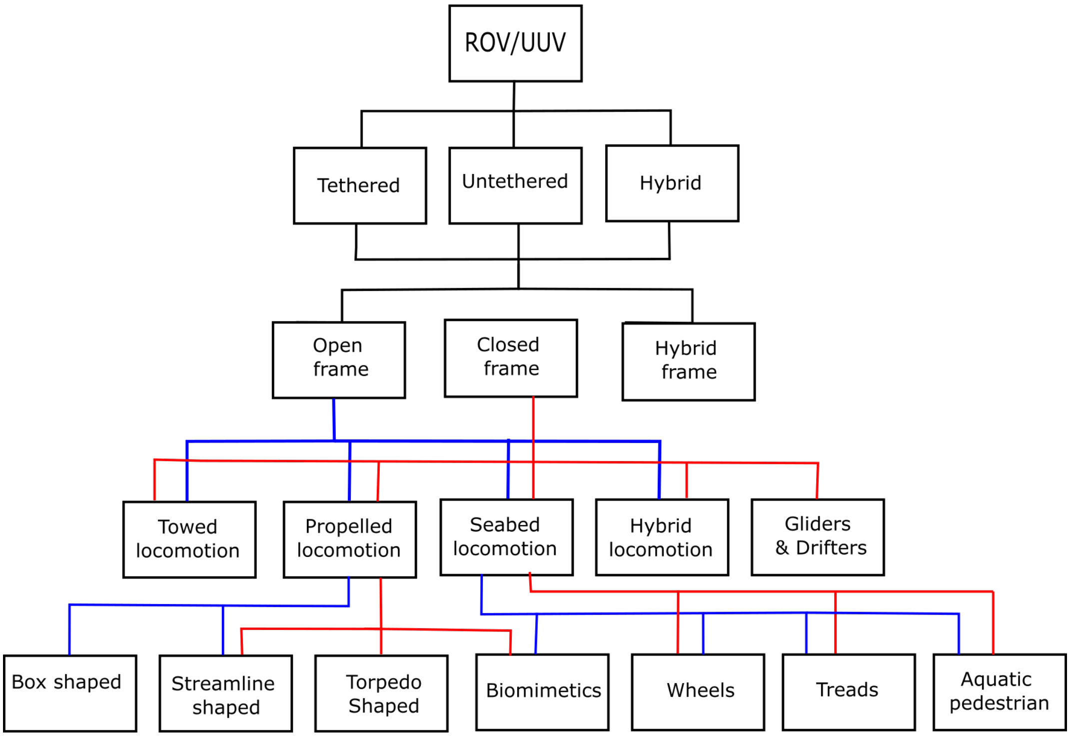
Today there are ROVs that can operate in both teleoperated mode (ROV) and autonomous modes (AUV). ROV LATIS is such an example, it is a next-generation smart ROV with unique features, including multiple modes of operation. These types of vehicles are today classified as Hybrid ROV as discussed earlier. In order to provide lucidity and distinctiveness to the subject of UUV and ROV classes, we present a classification taxonomy based on frame structure and locomotion, see Figure 5.

In water, one of the arguments for the justification of difference is the presence of the tether, this is due to the difficulty faced in underwater communication. With advancements in underwater communication, this will no longer hold true. Moreover, as we have seen earlier there are already ROVs with AUV characteristics which are currently called HROVs, although some researchers refer to this type of vehicle as an Autonomous ROV (AROV), as it was called by Ramos, Thieme and Yang (2020). Hegde et al. (2019) defined AROV as tethered/untethered underwater vehicles which can function autonomously.

The presence of the tether classifies AUV and ROV, but this is also bound to change in the future as underwater communication advances and it has been seen that with the current advancements, ROV can also be tetherless while in AUV mode. Using this parameter to characterise ROV and AUVs has not provided clarity thus far, mainly due to the rapidly changing nature of the UUV field. However, classifying ROV based on the frame structure and mode of locomotion will give a clear unambiguous classification framework for ROV and the UUV family.

As mentioned earlier, there are three modes of operation; teleoperated, autonomous and semi-autonomous ROV, and the subsequent sections demonstrated that this is not a sufficient criterion to differentiate AUVs from ROV because ROV can also possess autonomous capabilities and with the emergence of Hybrid ROV which can function in all three modes. This makes it difficult to classify. “it is a subsea vehicle, it doesn't

Figure 5: ROV Classification (Towed branch on both sides)



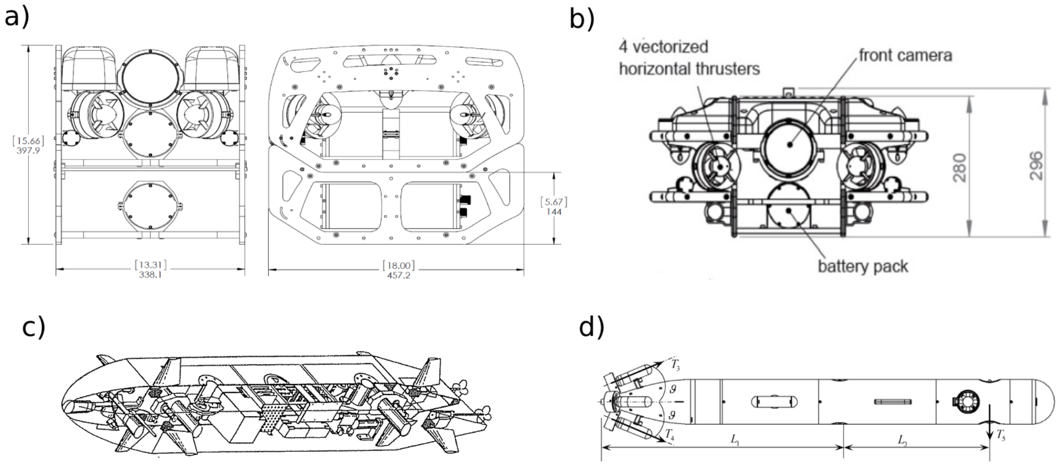
Source: Dalhatu et al. (2023)

matter as much" - Mr White, the vice president of subsea facilities engineering for Doris Engineering, to imply that the naming AUV or ROV does not matter as much due to innovations (WHITFIELD, 2017). 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 ROV to differentiate them. Therefore, we will use the terms ROV and UUV synonymously. When it comes to underwater robots, the medium of communication can either be tethered or untethered (wireless) or a vehicle that can have both, like the HROV. This provides the first branch of ROV/UUVs. We further classified the ROV based on their structure which can either be an open frame, closed frame or a hybrid frame that can change its shape with actuation. Figure 5 shows our proposed ROV taxonomy and figure 6 (a) and (b) show examples of open-frame structured ROVs.

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 Fig.6 (a) and (b). Open frames are capable of full actuation and instrumentation unlike closed frames and they can come in streamlined shapes (see Fig. 6 (b)) and in aquatic pedestrian forms.

Closed frame ROVs can come in five varieties: towed locomotion, propelled locomotion, seabed locomotion, and hybrid locomotion which is a mixture of two or more

Figure 6: Vehicle frames and shapes



Source: Dalhatu et al. (2023)

and gliders & drifters. An example of a closed frame can be seen in figure 6 (c) and (d). 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, these class can come in a torpedo shape (see figure 6 (d) or simply a streamlined shape (see figure 6 (c)) and in form of biomimetics (see figure 7).

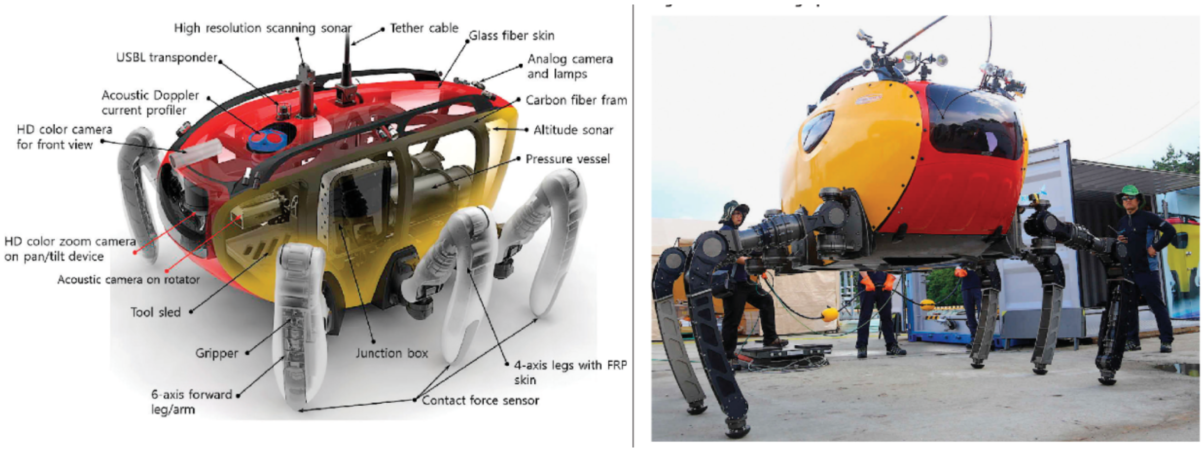
To the author's knowledge aquatic pedestrian ROVs are mainly closed frames thus far but open frames can also be in form of an aquatic pedestrian. Aquatic pedestrians are more suitable for underwater inspections and observations in terms of their movement that generates very low turbidity compared to propelled and treaded ROVs, an example of an aquatic pedestrian ROV is shown in Fig. 8.

Figure 7: Biomimetics (Left PoseiDrone, right One-legged demonstrator)

Source: Picardi et al. (2020)

Hybrid frames are frames that can transition from closed frames into open frames using actuators. This first appeared in the aquanaut HROV and can be seen in Figure 9. Hybrid frames are capable of concealing the actuation for the purpose of 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

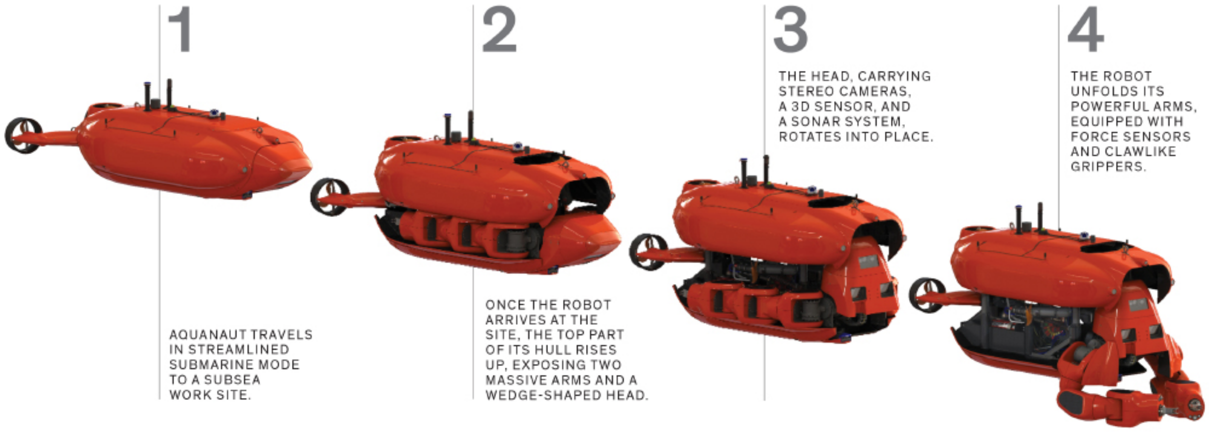
Figure 8: Aquatic pedestrian. A Seabed locomotion ROV type



Source: Jun and Shim (2014)

upon their state as they can only assume one form at a time.

Figure 9: Aquanaut ROV



Source: Manley et al. (2018)

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 while 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 seven kilometres per hour. 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 (PRIMEAU, 2019), it is radical innovations such as these that disrupt the current classifications. However, the classification provided in Fig. 5 utilises non-transitional parameters and therefore fits modern and future developments.

3 CHARACTERIZATION OF ROV SUBSYSTEMS

The field of ROVs has witnessed significant advancements in technology, revolutionizing underwater operations across various industries. This chapter explores the key technological aspects that enable the successful operation of ROVs in challenging underwater environments. ROVs are designed to perform a wide range of tasks, from inspection and maintenance to research and exploration. Understanding the technological components and systems that comprise ROVs is essential for appreciating their capabilities and potential applications.

3.1 Survey and Scanning Systems

Survey and scanning systems play a crucial role in the inspection and assessment of offshore steel structures and underwater environments (VELÁZQUEZ et al., 2022). Remotely Operated Vehicles (ROVs) are often employed to access and survey internal structures that are inaccessible to human divers (SCHUBERT et al., 2017).

One notable example of surveying technology used in underwater environments is 3D sonar. In the GOM-SCHEMA project, 3D sonar was utilized to gather data on the long-term impacts of oil spills on shipwreck preservation (DAMOUR et al., 2019). This technology provides detailed acoustic images of underwater structures, enabling accurate mapping and analysis of submerged objects.

In terms of ROV capabilities, the Nexus HROV (Highly-Responsive Remotely Operated Vehicle) stands out for its high maneuverability in deep dives, thanks to its lightweight fiber optic tether (YUH; MARANI; BLIDBERG, 2011). The use of a fiber optic tether facilitates efficient communication and data transmission between the ROV and the control station, enabling real-time monitoring and control of the vehicle's operations.

Another significant survey vehicle is the KAIKO 700II, which represents a complete ocean survey vehicle built upon the experience and design of the lost KAIKO 7000, a pioneering ocean survey vehicle from 1993 Nakajoh et al. (2016). The KAIKO 700II integrates advanced surveying instruments, such as sonar systems and cameras, to capture high-quality data for comprehensive underwater surveys.

The technical aspects of survey and scanning systems in ROVs encompass a range of sensors, instruments, and data processing capabilities. These systems include sonar devices, such as 3D sonar, that utilize sound waves to create detailed acoustic images of underwater structures. Cameras and imaging systems are employed to capture visual data for documentation and inspection purposes. Advanced image processing algorithms enable the analysis and interpretation of collected data, facilitating the identification of anomalies, corrosion, or other structural issues.

The integration of survey and scanning systems with ROVs enables efficient and precise data collection in challenging underwater environments. The use of advanced sensors and imaging technologies enhances the accuracy and quality of collected data, allowing for detailed assessments of offshore steel structures, shipwrecks, and other underwater features (CHEMISKY et al., 2021)

Furthermore, ongoing research and development efforts continue to improve survey and scanning systems for ROVs. Advancements in sensor technologies, such as higher-resolution imaging and multi-beam sonar systems, contribute to more detailed and comprehensive data acquisition. Enhanced data processing techniques, including artificial intelligence and machine learning algorithms, are being employed to automate data analysis, anomaly detection, and asset integrity assessment (XIA et al., 2023).

Survey and scanning systems are vital components of ROVs for underwater inspections and assessments. Utilizing technologies such as 3D sonar, cameras, and fiber optic tethers, these systems enable the collection of high-quality data for detailed mapping, analysis, and monitoring of underwater structures. Ongoing advancements in sensor technology and data processing techniques will further enhance the capabilities of survey and scanning systems, empowering ROVs to perform complex tasks and contribute to the maintenance and preservation of offshore assets.

Currently, virtual reality is used to improve video quality by superimposing it into a virtual environment (MUSTARD; STRAY, 2023). This increases visibility, safety and efficiency (PARENTE et al., 2019). Augmented Reality has been demonstrated by the 3D real-time augmented reality implemented through the LATIS ROV (OMERDIC et al., 2012). Augmented Reality was used in the gulf of Mexico in 2015 (PARENTE et al., 2019) and in 2016 (STEWART; RYDEN; COX, 2016).

Augmented Reality (AR) is a rapidly advancing technology that holds great potential for enhancing the capabilities of Remotely Operated Vehicles (ROVs) in underwater operations (PARENTE et al., 2019). While virtual reality is primarily used to improve video quality by superimposing it into a virtual environment, AR takes it a step further by overlaying virtual elements onto the real-world view, providing users with real-time information and enhancing their situational awareness.

In the context of ROVs, AR has shown promising applications in various aspects of underwater operations. One notable example is the implementation of 3D real-time augmented reality through the LATIS ROV (OMERDIC et al., 2012). This system utilizes AR to superimpose digital information, such as graphics, annotations, and data, onto the live video feed from the ROV's camera. By augmenting the real-time video stream with contextual information, operators can gain enhanced understanding and make more informed decisions during complex underwater tasks.

The use of AR in underwater operations has also been demonstrated in specific locations, such as the Gulf of Mexico. In 2015, AR technology was employed in the region, providing operators with augmented views of the underwater environment, enabling them to navigate and inspect structures with greater visibility, safety, and efficiency (PARENTE et al., 2019). Similarly, in 2016, AR was utilized in the Gulf of Mexico by Stewart, Ryden and Cox (2016), further showcasing the potential of this technology in enhancing ROV operations.

The benefits of AR in ROV operations are significant. By augmenting the operator's view with additional information, AR enhances situational awareness, enabling operators to better understand their surroundings and make informed decisions in real-time. It can assist in navigation, target identification, and precise positioning, allowing for more accurate and efficient inspection, maintenance, and intervention tasks. Furthermore, AR can contribute to improved safety by providing visual cues and warnings, highlighting potential hazards or anomalies that may not be easily visible in the raw video feed.

3.2 Umbilical and Tether Management System

One crucial aspect of operating Remotely Operated Vehicles (ROVs) is the management of the umbilical and tether system. The umbilical serves as a lifeline, connecting the ROV to the surface vessel and providing power, communication, and control signals. However, the weight and drag of the umbilical can become a challenge, particularly for larger ROVs. To address this, a Tether Management System (TMS) is employed to reduce the weight and drag by managing the deployment and retrieval of the umbilical (LUBIS; KIMIAEI; EFTHYMIOU, 2021).

The TMS plays a vital role in supporting the operations of larger ROVs. It utilizes various mechanisms and components to control the umbilical, ensuring that it is properly tensioned and managed during ROV operations. The TMS typically consists of winches, sheave systems, and guiding devices that enable the controlled deployment and recovery of the umbilical.

While the TMS helps in reducing the weight and drag of the umbilical, it introduces additional connections and components, which can increase the system's susceptibility to failures. Each connection point becomes a potential point of failure, and any malfunction or disconnection can disrupt the power, communication, or control signals between the ROV and the surface vessel (FARD et al., 2018). Therefore, it is crucial to design and engineer the TMS with reliability and robustness in mind, incorporating redundancy and fail-safe mechanisms to minimize the risk of failures (RESTIVO; GLENN; WILLIAMS, 2017).

3.3 Control Systems

The control systems of ROVs play a crucial role in enabling remote operation, precise maneuverability, and control over the vehicle's tools and sensors. These systems allow operators on the surface to navigate the ROV, control its movements, and perform various tasks with precision. The control systems comprise several key components and technologies that contribute to the overall functionality and performance of the ROV.

One essential aspect of ROV control systems is the user interface. Advanced control interfaces, such as joysticks, enable operators to intuitively and precisely control the ROV's actions. These interfaces provide a direct means of translating operator inputs into commands that the ROV can understand and execute. The joysticks allow operators to control the ROV's movements in different directions, adjust its depth, and manipulate its tools and sensors (ABDULLAH et al., 2018).

In addition to the control interface, the propulsion system is a vital component of ROV control systems. The propulsion system provides the necessary thrust and maneuverability for the ROV to navigate through water with ease and stability. ROVs typically employ either electric or hydraulic propulsion systems. Electric propulsion systems are commonly used in smaller ROVs due to their compactness, efficiency, and precise control capabilities. They rely on electric motors and propellers to generate thrust and enable maneuverability. On the other hand, hydraulic propulsion systems, which utilize hydraulic pumps and motors, are often found in larger ROVs that require more power and strength for operating in challenging underwater environments (HUO; WANG; GE, 2016).

The control systems of ROVs also incorporate feedback mechanisms and sensors to enhance control accuracy and stability. These feedback systems provide operators with real-time information about the ROV's position, orientation, and environmental conditions. By receiving feedback from sensors such as depth sensors, gyroscopes, and accelerometers, operators can make informed decisions and adjust the ROV's control inputs accordingly. This feedback loop ensures precise and responsive control over the vehicle's movements (GUPTA et al., 2006).

Furthermore, the control systems of ROVs may include additional features and technologies to enhance their functionality. For instance, some ROVs are equipped with autonomous or semi-autonomous capabilities, enabling them to perform predefined tasks or execute pre-programmed missions without constant manual control. These autonomous functions can improve the efficiency and safety of ROV operations, especially in repetitive or time-consuming tasks (TAN; LIU; CHEN, 2017).

The control systems of ROVs encompass various components and technologies that enable remote operation, precise maneuverability, and control over the vehicle's tools and sensors. Advanced control interfaces, propulsion systems (electric or hydraulic), feedback mechanisms, and autonomous capabilities are all integral parts of ROV control systems. These systems contribute to the overall efficiency, stability, and performance of ROVs in underwater operations, enabling operators to navigate the vehicle with precision and execute complex tasks in challenging environments.

3.4 Power and Propulsion

Power and propulsion systems are critical components of ROVs, ensuring their effective operation and maneuverability in underwater environments. These systems provide the necessary power to drive the vehicle and its various systems, allowing it to perform tasks and navigate through water with precision and stability.

ROVs can utilize either electrical or hydraulic power systems, depending on their specific requirements and operational needs. Electrical power systems typically rely on batteries or power supplied from the surface through umbilical cables (RITTER et al., 1997). Batteries are commonly used in smaller ROVs as they provide a portable and self-contained power source. These batteries are typically rechargeable and need to be replaced or recharged periodically during the mission to ensure continuous operation (WANG et al., 2012).

In contrast, larger ROVs often utilize power supplied from the surface through umbilical cables. The umbilical cables not only provide power but also serve as a communication link between the surface control station and the ROV. This configuration allows for continuous power supply, eliminating the need for battery replacements or recharging.

Hydraulic power systems, on the other hand, utilize fluid power for propulsion and operation of the ROV's systems. These systems typically consist of hydraulic pumps, motors, and actuators. The hydraulic fluid is pressurized by the surface-based hydraulic power unit and transmitted through hydraulic lines to various components on the ROV, enabling precise control of the vehicle's movements and the operation of its manipulator arms and other hydraulic-driven tools.

Propulsion systems are responsible for generating thrust and enabling the ROV to move in different directions. Common propulsion systems used in ROVsinclude thrusters and propellers. Thrusters are often used in electrically powered ROVs and provide omnidirectional control by independently adjusting the thrust from multiple thrusters. This allows for precise maneuverability and stabilization in challenging underwater conditions (PUGI; ALLOTTA; PAGLIAI, 2018).

Propellers, on the other hand, are commonly found in hydraulic-powered ROVs. They use hydraulic power to drive the rotation of the propeller blades, creating forward or backward thrust. The propellers can be orientated to direct the thrust and allow the ROV to move in various directions. Some ROVs may also incorporate additional thrusters or propellers to enhance maneuverability, stability, and dynamic positioning capabilities (ZHU et al., 2012).

The power and propulsion systems of ROVs are essential for their successful operation underwater. Electrical or hydraulic power systems provide the necessary power to drive the vehicle and its systems, while propulsion systems such as thrusters or propellers enable precise movement control and the maintenance of position in challenging underwater conditions. These systems are designed to ensure reliable and efficient performance, allowing ROVs to fulfill their intended tasks in a range of underwater applications.

3.5 Communication Systems

Effective communication between the ROV and surface operators is of utmost importance for real-time control, monitoring, and data transmission in underwater operations. ROVs are typically connected to the surface control station through umbilical cables, which serve as the lifeline for communication and power transfer. Various communication methods and technologies have been employed to enhance the capabilities of ROVs in different operational scenarios.

One essential component of the communication system is the use of fiber-optic cables within the umbilical (CAPOCCI et al., 2017). Fiber optics provide high-speed data transfer capabilities, enabling operators to receive live video feeds, sensor data, and other critical information from the ROV in real-time. Fiber optics offer advantages such as high bandwidth, low latency, and immunity to electromagnetic interference, ensuring reliable and efficient communication between the ROV and the surface (BOWEN et al., 2009).

In situations where direct cable connections are impractical or not feasible, wireless communication technologies are employed to bridge the gap between the ROV and the surface control station. One commonly used wireless communication method is acoustic modems. Acoustic modems utilize sound waves to transmit data through water, offering a reliable means of communication in underwater environments. These modems can be integrated into the ROV and the surface control station, allowing for bidirectional data exchange (KIM; PARK, 2012).

Acoustic modems operate by converting digital signals into acoustic waves that propagate through water. The receiver on the other end captures the acoustic signals and converts them back into digital data (JOBY, 2022). This wireless communication method enables operators to remotely control the ROV, receive status updates, and transmit commands and instructions. Although acoustic communication has slower data rates compared to fiber optics, it provides a practical solution for situations where physical cable connections are not feasible, such as in deep-sea operations or when the ROV needs to be deployed over long distances.

Satellite communication is also used in ROVs. The Ames research centre conducted an experiment in 1993 where they controlled an ROV via satellite to study the seafloor ecology in Antarctica (STOKER et al., 1995).

The world wide web has the capability to provide us with a truly distributed robotic system by making it available to a vast number of people. The first world wide web teleoperated robot was the mercury project developed in 1994 (GOLDBERG et al., 1995). A telerobot developed in Australia, demonstrated that internet-based teleoperation can easily be used with ROVs in unknown unstructured environments (BRUZZONE et al., 2004).

Statoil has also demonstrated that ROVs can also be controlled via satellite connections and semiautomatic systems are used to control ROVs. In 2015 Oceaneering also demonstrated the piloting of a work-class ROV via a satellite link (RASSENFOSS, 2016).

Regarding ROV Interfacing, a new purpose-built ROV system was built with a fully integrated ROV interface system to be able to handle the specific work requirements of Garden Banks Block 388 (GB 388) in the U.S Gulf of Mexico where the project needed ROV support (GRANHAUG; BREWSTER, 1995). The success of Popeye's project has allowed for several technological advancements which depended on effective ROV intervention to be implemented with no significant difficulties. The Popeye Project helped advance the technology and standardization of ROV interfaces for deepwater subsea production systems (HERNANDEZ; HICKOK et al., 1996). The Mensa project subsea system used ROV interface by designing the tools and all the subsea equipment were designed for ROV intervention. The Mensa project has also shown that configuring the ROV to perform multiple tasks in a single dive saves both time and money (HERNANDEZ et al., 1998).

ROV communication encompasses various methods and technologies, including satellite communication, internet-based teleoperation, and purpose-built ROV interfaces. These advancements have extended the capabilities of ROVs, enabling remote control, real-time data transmission, and integration into subsea systems. The integration of satellite communication and internet-based control has expanded the operational range and flexibility of ROVs, while purpose-built interfaces have improved the efficiency and effectiveness of ROV interventions in subsea operations. Continued advancements in ROV communication technologies will further enhance the capabilities and possibilities of these underwater vehicles in diverse applications.

Effective communication between the ROV and surface operators is facilitated through umbilical cables, which house communication channels. Fiber-optic cables provide high-speed data transfer, allowing for real-time video feeds and sensor data transmission. Wireless communication technologies, such as acoustic modems, are employed when direct cable connections are not feasible. These communication systems enable operators to control the ROV, receive live video feeds, monitor sensor data, and exchange commands and instructions. The use of data processing techniques, protocols, and telemetry capabilities further enhances the efficiency and reliability of the communication system in ROV operations.

3.6 Cameras and Sensors

ROVs rely on a combination of high-resolution cameras and a diverse array of sensors to gather valuable visual and environmental data from the underwater environment. These sensors and cameras play a critical role in providing operators with essential information for navigation, inspection, and scientific research purposes.

High-resolution cameras are an integral part of the ROV's sensor suite, enabling operators to capture clear and detailed images of the underwater surroundings. These cameras are strategically positioned on the ROV to provide various perspectives and angles, allowing operators to assess the condition of underwater structures, identify potential hazards, and monitor the progress of specific tasks. The cameras can be equipped with features such as zoom capabilities, pan-tilt functionality, and adjustable lighting configurations to optimize image quality and clarity in different underwater conditions (ROMAN; INGLIS; RUTTER, 2010).

In addition to cameras, ROVs are equipped with a range of specialized sensors that enable them to collect environmental data and gather insights about the underwater surroundings. Sonar systems, for example, employ sound waves to create detailed maps of the seafloor, detect objects, and provide information on water depth and underwater topography. These sonar systems can be of various types, including multibeam sonars that provide high-resolution three-dimensional mapping capabilities or side-scan sonars that produce detailed images of the seafloor and objects in the water column (AHMAD et al., 2010).

Depth sensors are another vital component of the ROV's sensor suite, allowing operators to precisely determine the ROV's depth in the water column. These sensors utilize pressure measurements to calculate the depth and provide operators with crucial information for maintaining proper positioning and executing tasks at specific depths (ROMAN et al., 2012).

Temperature sensors are often integrated into ROVs to monitor and record water temperature variations at different depths. These sensors play a crucial role in environmental monitoring, underwater research, and scientific studies, providing valuable data on temperature gradients and thermal characteristics of the underwater environment (LA-

GADEC; PRIGENT; LAFONTAINE, 2019).

Furthermore, ROVs can be equipped with additional specialized instruments and sensors tailored to specific mission requirements. These instruments may include water samplers, water quality analyzers, hydrocarbon sensors, or biological sampling devices, among others. These specialized sensors enable the ROV to conduct detailed environmental assessments, collect samples for analysis, and gather specific data relevant to scientific research or inspection tasks.

To enhance data collection capabilities, advanced imaging technologies are integrated into some ROV systems. For instance, 3D mapping technologies enable the creation of detailed three-dimensional models of underwater structures and terrain. These mapping techniques utilize a combination of cameras, lasers, or sonar systems to capture precise measurements and geometric data, resulting in accurate representations of the underwater environment (DAMOUR et al., 2019).

ROVs rely on a combination of high-resolution cameras and a diverse range of sensors to gather visual and environmental data from the underwater environment. These sensors, including sonars, depth sensors, temperature sensors, and specialized instruments, enhance the ROV's capabilities to assess underwater conditions, detect objects of interest, and conduct scientific research. The integration of advanced imaging technologies further enhances the ROV's data collection capabilities, providing operators with detailed visual information and precise environmental data for effective navigation, inspection, and research purposes.

3.7 Manipulator Arms

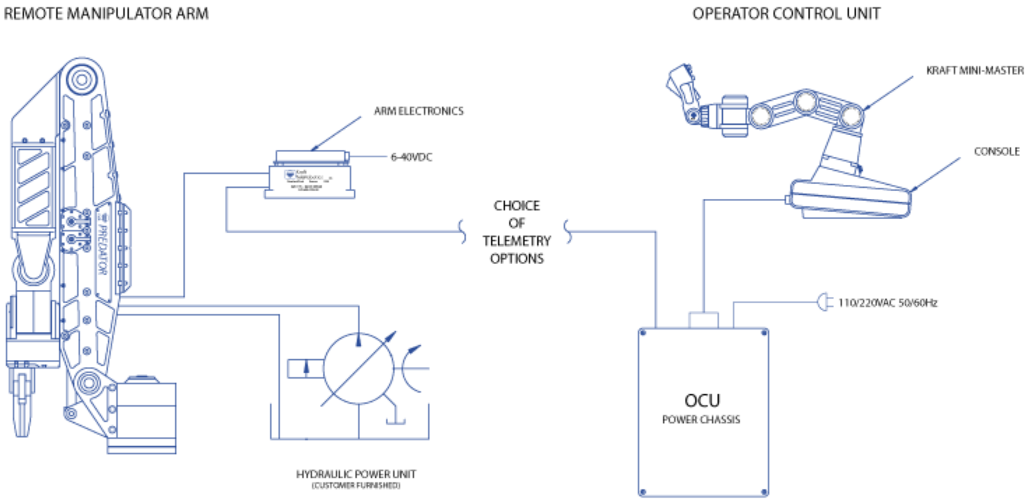
Manipulator arms play a crucial role in the functionality and versatility of ROVs. These arms are designed to remotely manipulate objects, perform tasks, and conduct various operations underwater. Operators on the surface control the manipulator arms, which are equipped with a range of tools and grippers, enabling the ROV to perform complex tasks and interact with the underwater environment.

The manipulator arms of ROVs are typically articulated mechanical systems that replicate the movements of a human arm. They consist of multiple joints that provide flexibility and allow for a wide range of motion. The joints are actuated by hydraulic or electric motors, depending on the power system used by the ROV (TEIGLAND; MØLLER; HASSANI, 2022).

The design and capabilities of the manipulator arms vary depending on the specific requirements of the ROV and the tasks it is intended to perform. Some manipulator arms feature multiple degrees of freedom, allowing for increased dexterity and precise control. They can perform actions such as rotating, extending, retracting, and gripping objects of various shapes and sizes (TEIGLAND; MØLLER; HASSANI, 2022).

The tools and grippers attached to the manipulator arms are designed to accommodate different tasks. They can include cutting tools, sample collection devices, cameras, sensors, and specialized instruments for specific operations. These tools are usually interchangeable, allowing operators to customize the manipulator arm's functionality based on the mission's requirements (MAZZEO et al., 2022).

Figure 10: Predator Force Feedback Manipulator



Source: Kraft Telerobotics [1]

To enhance control and feedback, modern manipulator arms often incorporate advanced technologies. This may include force feedback systems that provide operators with a sense of touch, allowing them to feel the forces exerted by the manipulator arm and make adjustments accordingly. Additionally, cameras and sensors integrated into the manipulator arms provide visual feedback to operators, aiding in precise positioning and manipulation of objects (PENG et al., 2023).

The manipulator arms of ROVs are versatile tools that enable the vehicles to perform a wide range of tasks and interact with the underwater environment effectively. Their dexterity, precision, and adaptability make them invaluable for various applications, from scientific research and exploration to industrial operations and subsea infrastructure maintenance.

3.8 Lighting Systems

Underwater visibility poses a significant challenge for ROV operations, as natural light diminishes rapidly with increasing water depth. To overcome this limitation, ROVs are equipped with powerful lighting systems that illuminate the surrounding environment. These lighting systems play a crucial role in ensuring clear visibility for both the operators controlling the ROV and the cameras used for capturing images and videos (CHEMISKY et al., 2021).

The lighting systems used in ROVs typically employ high-intensity LEDs (Light-Emitting Diodes) or halogen lamps (NISHIDA et al., 2021). LEDs are commonly preferred due to their energy efficiency, compact size, and long operational lifespan. They provide bright, focused illumination that enhances visibility in the underwater environment. Halogen lamps, on the other hand, have been traditionally used and offer a broader spectrum of light but are less energy-efficient compared to LEDs.The lighting systems in ROVs are typically operated remotely by the operators controlling the vehicle. They can adjust the brightness and direction of the lights based on the specific requirements of the mission. This capability is particularly useful when conducting inspections, surveys, or scientific research where capturing detailed visual information is critical.

It is worth noting that the choice of lighting system depends on the specific application and operating conditions. For example, in environments with high levels of particulate matter or turbidity, additional measures may be required, such as the use of specialized filters or auxiliary lighting sources, to improve visibility and mitigate the impact of suspended particles on image quality.

The lighting systems employed in ROVs are essential for overcoming the limited visibility in the underwater environment. High-intensity LEDs or halogen lamps provide bright illumination to ensure clear visibility for both operators and cameras. Adjustable lighting configurations and strategic positioning of the lights enable operators to adapt to varying lighting conditions, enhancing the quality of captured images and videos. By illuminating the underwater surroundings, ROV lighting systems facilitate safer and more effective operations, enabling operators to navigate, inspect, and collect valuable data in challenging underwater environments (MYINT et al., 2019).

3.9 Navigation and Positioning Systems

Accurate navigation and positioning are vital for the effective operation of ROVs in underwater environments. Traditional Global Positioning System (GPS) signals are unable to penetrate water, making them ineffective for providing real-time positioning information. As a result, alternative technologies are employed to ensure reliable and precise positioning for ROVs (QIN et al., 2022).

One commonly used technology for underwater positioning is the Doppler Velocity Log (DVL). A DVL utilizes the Doppler effect to measure the velocity of the ROV relative to the seabed. It operates by emitting acoustic pulses and measuring the frequency shift of the reflected signals to determine the ROV's velocity. By integrating the velocity measurements over time, the DVL can calculate the ROV's position relative to a known starting point. DVL systems provide accurate velocity and positioning data, enabling the ROV to maintain its position and navigate through complex underwater structures (QIN et al., 2022).

In addition to DVL, inertial navigation systems (INS) play a crucial role in ROV navigation. INS utilizes a combination of accelerometers, gyroscopes, and sometimes magnetometers to measure the ROV's acceleration, angular velocity, and magnetic field orientation. These sensors provide continuous measurements that are integrated over time to determine the ROV's position, velocity, and orientation. INS systems are highly accurate but are subject to drift over time. To mitigate this drift, INS can be aided by external positioning systems such as DVL or by periodic recalibration using known reference points (QIN et al., 2022).

Accurate navigation and positioning are crucial for the effective operation of ROVs. While traditional GPS signals are ineffective underwater, alternative technologies such as DVL and inertial navigation systems are employed. These systems provide real-time positioning information, allowing ROVs to maintain their position, navigate complex structures, and execute precise movements as commanded by operators. The fusion of data from multiple sensors further enhances accuracy, ensuring the ROV's ability to perform tasks with precision and efficiency in challenging underwater environments.

The technological aspects discussed in this chapter form the foundation of ROV capabilities and advancements. The control systems, power and propulsion, communication systems, cameras and sensors, manipulator arms, lighting systems, navigation and positioning systems, collectively contribute to the successful operation of ROVs in diverse underwater scenarios. Further research and innovation in these areas will continue to drive the evolution of ROV technology, unlocking new possibilities for underwater exploration, resource exploitation, and scientific discovery.

4 ROV APPLICATION IN OFFSHORE

4.1 ROV Inspection techniques

Inspection can either be internal or external. Internal inspection is normally performed by intelligent pigs using NDT techniques to detect, locate and characterize pipeline anomalies. The focus of this research is on the external forms of inspection that are executed utilising ROVs. The external inspection looks at the condition from the outside and it is the focus of this section. This section discusses the inspection techniques utilised.

NDT sensors are sensors that use a series of techniques where they are used to test structural flaws without causing any damage through direct or indirect means. They include acoustic, electromagnetic field, radiographic, and other active and/or passive physical stimulation. The most commonly used underwater NDT techniques are; Alternating Current Field Measurement Testing (ACFM), Magnetic Particle Testing (MPI), Eddy-Current Testing (ECT), Ultrasonic Testing (UT), Radiographic Testing (RT), Visual Testing (VT) Acoustic Emission Test (AET) (ZAWAWI et al., 2019). These techniques have their pros and cons, hence, a single NDT does not tell the entire story which is why a sensor array is usually deployed to test various parameters so that the faults can be fully characterized. It is called multiple inspection NDT when more than one of the methods is used, companies use it to increase efficiency because it provides more information about the asset being inspected (DALHATU et al., 2021). Each of the NDTs has its strengths and weaknesses and requires the skill of the operator to gather and interpret the data (CHRIST; SR, 2013). NDT techniques can be grouped into acoustic methods, electromagnetics methods and electrical methods (DALHATU et al., 2021).

ROVs are often equipped with a range of sensors that shall be described in the following sections. A staggering amount of technologies are used and are being developed for inspections of subsea assets, this section will cover some of the most popular techniques. There are simple inspection tasks and advanced inspection tasks. Simple inspection tasks do not require instrumentation, they utilise the standard parts of the ROV such as the camera, lights, sonar etc and are non-contact inspection techniques. However, this section's focus is advanced contact-based inspections. The advanced inspection also extends to environmental monitoring tasks such as water column monitoring, general oil spill detection, and sensor harvesting from autonomous wireless nodes placed on the seabed. etc., but this is out of the scope of this dissertation.

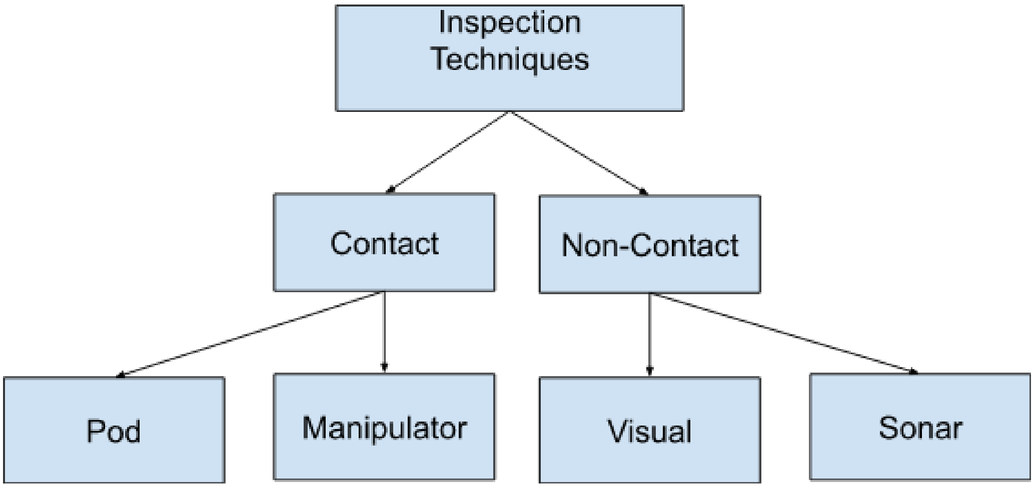
In this study, we classify different ROV inspection techniques into the following categories: Contact technique - Pod and Manipulator, and Non-contact technique. A detailed classification of these techniques is shown in Fig. 11. Advanced contact-based inspection techniques were mostly taken directly taken from standard onshore NDT and applied in underwater conditions with some modifications (SHUKLA; KARKI, 2016). Because the current in-air (outside water) inspection methodologies are also used for in-water (in-situ) inspections. Most of the methodologies are suitable for mobile offshore drilling units (MODUs), permanent floating production units (FPUs), SPSs, risers and pipelines.

But challenges are faced due to the unstable underwater environment. Underwater, they fail to function properly due to tidal conditions, marine growth and difficult visibility hamper the achievement of the full efficiency of the systems under non-stable and unpredictable conditions. Modifications had to be done. Environmental uncertainties together with the technique's limitation give rise to inaccuracies in the results, therefore to compensate for such limitations multiple uses of NDT techniques have been suggested by researchers to provide more accurate results. As an example, researchers have proposed a teleoperated device known as ARMS. This innovative system integrates a slave manipulator into the ROV, providing the operator with real-time 'force-feedback.' This means that the operator can feel the forces and resistance encountered by the manipulator while remotely controlling it. This advanced feature enhances decision-making capabilities, even in situations with limited visual clarity or challenging environmental conditions. The incorporation of force-feedback has shown significant utility, particularly when used in conjunction with Non-Destructive Testing (NDT) devices during ROV inspections. (CHRIST; SR, 2013).

4.1.1 Contact based Techniques

This technique consists of two types: Pod-based and Manipulator-based techniques. The output of these techniques can either be signal-based or Visual based. The signal-based outputs a signal in form of waveforms for interpretation while the visual type gives a visual representation of the defects on the material being inspected. The following

Figure 11: Inspection techniques



Source: (Own work)

techniques are utilised for contact based inspection:

Alternating Current Field Measurement : Recently ACFM has become the weapon of choice in the subsea environment, in this technique alternating current is induced into the metal surface which produces a uniform magnetic field above the surface until a non-uniformity on the metal produces a perturbation in this field forcing it to flow around the fault, and then the magnetic field variation is mapped to measure the depth and size of the fault (CHRIST; SR, 2013). Immediate defect, depth and size can be achieved by the use of ACFM and the amount of missed and spurious signals is significantly low in ACFM compared to MPI and ECT and it has been routinely used by oil and gas in structural weld inspections (ZAWAWI et al., 2019). it has also been used in PETROBRAS for routine structural inspection of the offshore platforms (RIZZO, 2013). With ACFM there is a lower cleaning requirement but the inspections of welds repair can cause spurious indications, and the presence of multiple defects can reduce the chances of depth estimation (ZAWAWI et al., 2019).

Ultrasonic testing Ultrasonic testing involves sending ultrasonic beams through the structure which then reflect the waves to be received by the receiver. They use piezoelectric probes. These piezoelectric elements vibrate to generate mechanical waves of 1MHz to 10MHz it is used to inspect corrosion by measuring the wall thickness as well as fatigue crack. However, the readings are subject to a host of errors and interpretations, to achieve a higher accuracy modern UT gauges make use of high multiple echo technique (CHRIST; SR, 2013). The sound that travels within a metal resonated at a frequency which allows and there is an echo bounce, this allows for more accurate measurement with regards to the metal versus other things like coatings and dirt by isolating the sound timing within the metal (CHRIST; SR, 2013). The things that attenuate sound travelling through the metal in water are the discontinuities. The type of the material determines the speed at which the sound travels through it, in steel the sound travels at 16,400 ft/s (5000 m/s) when this steel is submerged in the water a high level of sound attenuation is experienced. In a homogeneous metal, longitudinal waves travel evenly and when there is a presence of any break or internal flaws this acoustic energy gets dissipated thus revealing the flaw (CHRIST; SR, 2013).

Eddy Current Testing Eddy current is one of the most efficient methods used to diagnose the safety condition and identify the material of a particle (MUN; KIM, 2014). ECT works based on the principle of electromagnetism, it makes use of electrical current induction through the structure to magnetize it, (Faradays Law of electromagnetic induction) which then during its demagnetization a current known as eddy current is generated, then disturbs the time-varying magnetic fields by Lenz's law creating a new time-varying magnetic field which then determines the total magnetic fields interlinking the coils, as a result of this in the probe coil the overall magnetic field varies the impedance of the probe coil through changing the flow of the current, it is this change in impedance the state and the location of the defects in the structure. This method has a limited depth penetration. Eddy current is effective in determining the status of the abnormalities of the surface of metals, ECT uses two types of probes, one that generates the magnetic field and one that receives the generated magnetic field, it has various types of testing probes such as impedance probe, T/R probe, and T/T probe (MUN; KIM, 2014) and the impedance probe has proven to produce better results.

Magnetic Particle Inspection : MPI can be regarded as the standard method for locating and characterizing the length of a surface-breaking crack but has been superseded by other NDT methods to some extent. In this NDT the structure is magnetized and a dry powder from ferromagnetic particles or in its liquid form (ink) is applied which the generated magnetic field affects to cause a visual appearance of the magnetic flux leakage and the flaw is detected. This is a very difficult method to apply underwater because there is a need to isolate it from water. There are three types of this magnetism; Ferromagnetism, paramagnetism and diamagnetism magnetism can be induced in a material in one of the 3 ways; applying a permanent magnet, passing a current through the material or inductance by a current-carrying inductor near the subject (CHRIST; SR, 2013).

The need to apply the magnetic particle through water and its turbidity may limit visibility significantly. In this method it is essential to clean the surface thoroughly to bare metal and operations at shallow depths may encounter light-level problems unless high visibility inks are used or the inspection is done at night. Considerable care must be taken when cleaning to peen over the edges of any defect that might be present. This method requires a close visual inspection before and during the operation because fabrication defects such as weld undercuts, inter bead grooves etc. are often mistaken for cracks. The detection system involves the use of magnetic particles stored as a suspension in liquid and fed through a hose to the examination area being magnetized. The florescent in the container is slightly over-pressured or fitted with a pump to supply the ink, to avoid settling of the particles the ink is agitated frequently. To view the result ultraviolet light is used. Sometimes non-fluorescent inks are used for inspection.

Magnetic Flux Leakage : In this method of NDT, the structure is magnetized and if the structure has any defect, the magnetic field is deviated and hence magnetic flux leakage which is then detected by the receiver coil to indicate the flaw. The output of the detector is filtered and amplified for better results. The magnetization of ropes often surrounds the rope under test as can be seen in figure 10 Sukhorukov, Slesarev and Vorontsov (2014) it is made of two halves made of permanent magnets that surround the rope. This method is mostly used to detect corrosion flaws and the maximum wall thickness that can be tested is 10-15mm. Hedayati et al. (2010) developed a small low-cost ROV with dedicated electromagnetic flux leakage searching arms intended for inspecting the outer space of an FPSO and a ship hull. Magnetic flux leakage has been used for steel wire inspection for decades and new challenges have come from offshore mining and oil and gas drilling and their request came for rope monitoring (SUKHORUKOV; SLESAREV; VORONTSOV, 2014)

Acoustic Emission Testing This method works based on the high-frequency elastic waves emitted from the flawed source in the material which is under stress or deformation, this emitted frequency gets picked up by piezoelectric transducers and converted into an electrical signal which gets amplified by an external amplifier, filtered from external noises and processed. This method is used to detect, locate and characterize damage, including weld monitoring, detecting leakages, cracks forming in pressure vessels, and corrosion estimation in reinforced concrete structures and pipelines transporting liquids at high pressure. It is a powerful tool for examining materials that deform under stress. It is widely used for condition monitoring in the air and has shown great potential for monitoring mooring ropes underwater (BASHIR et al., 2017). These emissions are a phenomenon of radiation of acoustic waves in solids when materials undergo irreversible changes in their internal structure as a result of crack formations or ageing, temperature gradients or some other external forces (ZAWAWI et al., 2019). There are three major areas where AE is applied; source location, material mechanical performance and health monitoring (ZAWAWI et al., 2019).

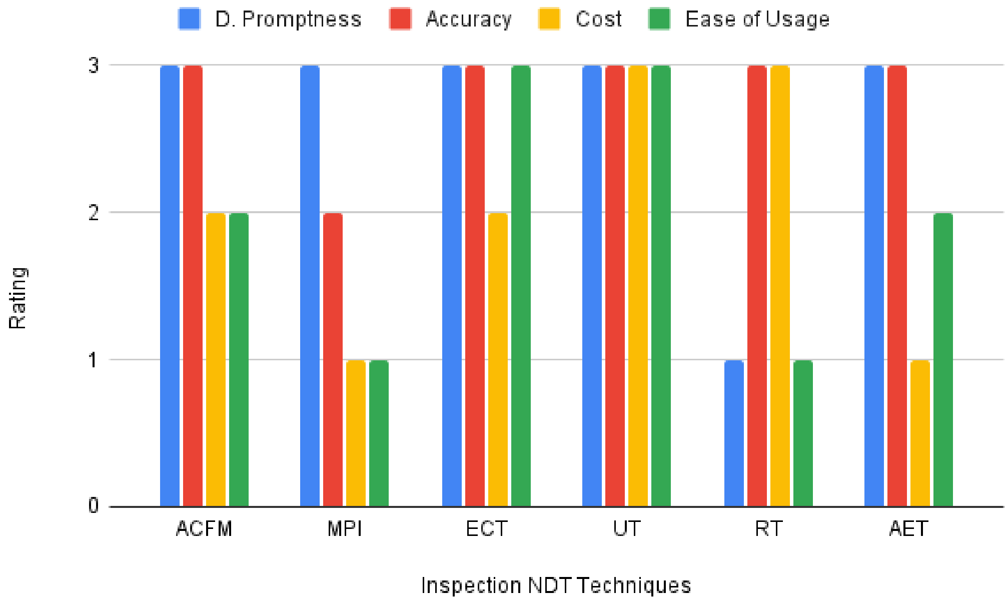
Radiographic testing Radiographic testing (RT) is based on short-wavelength electromagnetic radiation in order to penetrate a structure of the material. A tested part is placed between the radiation source and the radiation-sensitive film. It is a very sensitive method, which is used to inspect hidden areas since direct access is not necessary. Nonetheless, RT has several disadvantages, e.g. hazards associated with radiation in old radiographic devices high cost of testing equipment, and the time-absorbing process due to its long duration of exposure. Moreover, the depth of discontinuities is not measured and testing requires two-sided access to the component. RT remains insensitive if the direction of damage is the same as the direction of penetrated radiation. The polymer matrix composite materials are weakly penetrated by some radioactive isotopes. RT is used to inspect the condition of pipelines, e.g under deep water offshore gas and oil pipelines.

An improved version of a conventional RT method is X-ray Computed Tomography (CT), which provides a 3D image as a result of testing a structure with a very high resolution. The main strength of X-ray CT is the capability of the volumetric representation of a tested element. Nevertheless, the very high cost of inspection and limitations to laboratory conditions are crucial drawbacks of this technique. Silva et al. (2021) provides a comparative study and measurements of the three techniques Digital Radiography (DR) with Digital Detector Arrays (DDA), Coplanar Translational Laminography (CTL) and Computed Tomography (CT), applied for composite pipeline inspection. It is demonstrated that CTL and CT provide advantages for the evaluation of pipe-to-pipe connections and the evaluation of adhesive applications.

4.1.2 Comparison of the Contact based Techniques

A qualitative performance analysis of various manipulator-based inspection techniques based on the literature cited above is presented here. The performance criteria considered are detection promptness, operational cost, accuracy and ease of operation. The analysis is performed by rating the criteria into high, medium and low to compare their performance on a bar chart that represents the strenghts and weaknesses of the techniques.As it can be seen, the techniques posses propmtness and accuracy with the exception of MPI and RT, MPI has a medium accuracy rating because it has low sensitivity to detect cracks that run parallel to the magnetic field and deeply embedded flaws cannot be detected. MPI is also difficult to use underwater due to the need for its isolation from water, turbidity affecting the visibility significantly and the need for thorough cleaning of the surface to bear metal. ECT and UT have the most ease of usage, however, UT has a high cost due to the cost of the equipment. In terms of best performance, regardless of cost, UT is the best not in terms of cost savings and maximum possible performance ACFM and ECT would be a better choice. ECT has better ease of usage compared to ACFM. ECT is used for surface and near-surface defects while ACFM is used to detect surface-level cracks.

Figure 12: Three-level performance analysis comparison



Source: (Own work)

4.1.3 Manipulator based

Manipulator-based NDTs are generally those techniques that can be applied by using a probe, see Fig. 13. ACFM for example is performed by using a probe and there are three methods of underwater ACFM; diver mimicking, pick and place probes or array probe deployment. Probe movement and speed are not critical in ACFM and this can be replicated with the ROV manipulator but the weld must be followed because the probe has a certain scan scanning area and it is not easy to carry out complicated curves of welds in offshore platforms because of complications that come with keeping the ROV fixed on the worksite (LUGG, 2011). Small probes give an advantage because they allow you to get into tight places but small probes can easily be damaged due to the stability issues of the ROV. To get around this problem the second method is used which is the pick and place, it is a row of sensors that are aligned to the direction of the weld, the manipulator places the probe on the weld and reads the data and then places it again in the next position reading the data in big large chunks.

Figure 13: Alternating Current Field Measurement

Source: Lugg (2011)

A problem is however presented with regards to the shape of the probes, a flat probe inspecting a curved surface is a mismatch and analysis can become difficult when long defects cannot be detected in a single placement and software had to be made to merge the data for proper analysis.

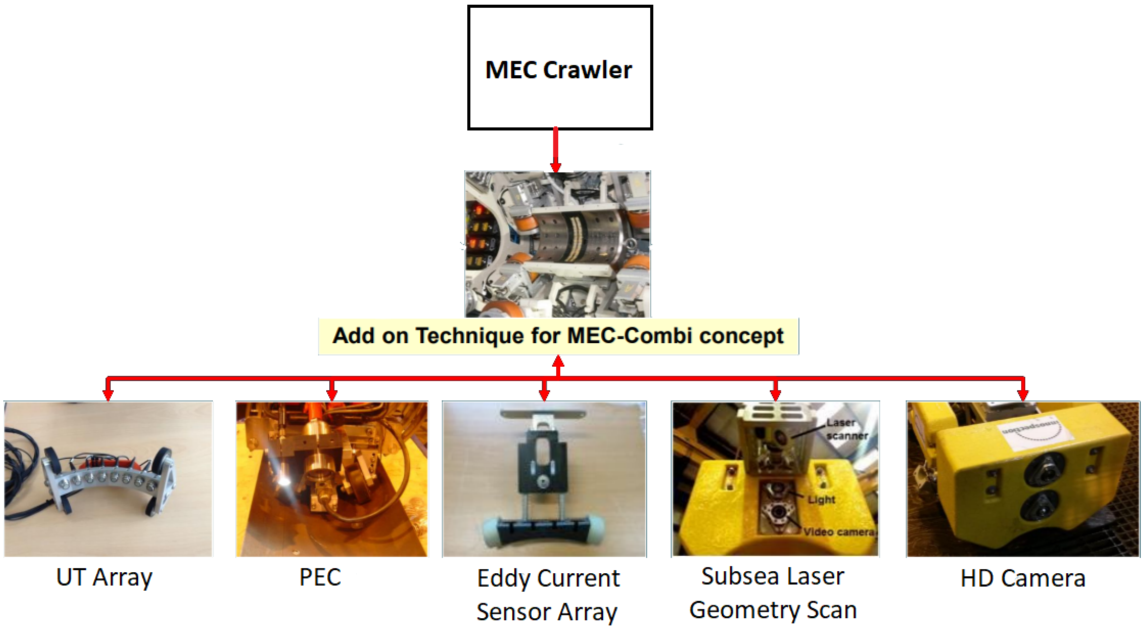
As can be seen, manipulator-based NDT application comes with stability challenges of the ROV and manipulator dexterity problems. For these reasons Pod-based tools were developed which are placed by the ROV manipulator and the probe movement is done by the scanner frame instead of the manipulator (LUGG, 2011).

4.1.4 Pod based

The pod-based inspection comes in two varieties: Locomotive which consists of crawlers integrated with motors for independent movement along a pipe or riser and non-locomotive which is tugged (moved along the pipe or riser) by an ROV.

Locomotive For cases where a pipeline is deemed unpiggable and ROVs are not being used for tugging, an external pipeline crawler with integrated motors may be used. Like intelligent pigs, external pipeline crawlers can carry a range of inspection tools that can determine the health status of the pipeline. Different models of pipeline crawlers may scan the pipeline via axial measurements (thus requiring multiple passes) or circumferential measurements (HO et al., 2020).

Figure 14: Magnetic Eddy Current Crawler add on



Source: (Own work)

Despite the availability of various inspection techniques, inspection and integrity management is not without challenges. For example, Flexible risers and flexible pipes have various layers and types of material which pose challenges which inspection techniques are able to inspect only the near side armour layers for wire disruptions, but the far side armour layer remains uninspected. Ultrasonic technologies could be used to inspect these far sides but this requires flooding of the annulus with a complaint for the inspection to be performed and this presents a potential risk of damage, especially to the inner layers of the flexible risers. Hence.

the market showed a clear demand for a new type of inspection technology capable of delivering an external fast screening of flexible risers in-situ without the risk of damage from annulus flooding. To meet this demand tools like the innospection MEC-FIT were developed, MEC stands for Magnetic Eddy Current and it is a variation of eddy current testing which allows finding flaws in the volume also of thick ferritic steel components.

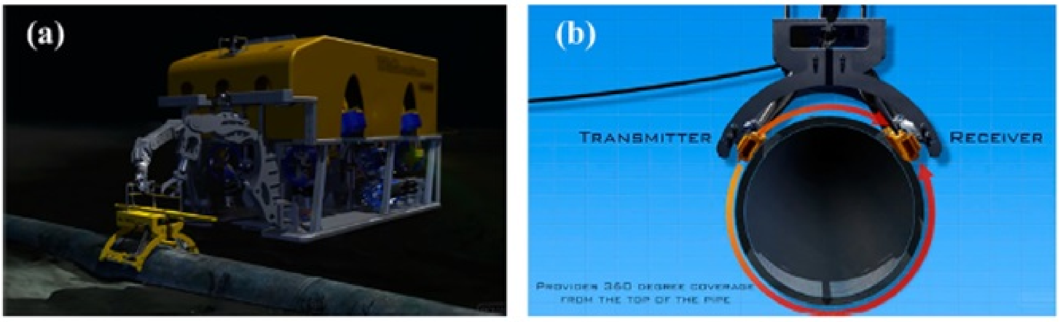
Innospection Ltd. MEC-FIT Flexible Riser Inspection system uses a special eddy current system that can control the field strength for the inspection of the surface of conventional and flexible risers. Deployed by an ROV, MEC-FIT is attached to the outer surface of risers and can detect localized flaws such as corrosion, cracks, general wall loss and, potentially, fatigue.

Figure 14 shows the Add on tools; UT array, Eddy current sensor array, Subsea laser geometry scan, HD camera and Pulsed Eddy Current (PEC), that can be used on a Magnetic Eddy Current (MEC) Crawler from Innospection company. PEC works using the principle of electromagnetic induction. When applying step function voltage to a conductor, a magnetic field develops around it. This field changes in intensity as the current alternates. If brought close to the first field, another conductor will have a current induced in it as well. If there are any flaws in this material then the eddy current will distort. In the case of PEC, the first conductor is an eddy current probe. The second is the test material. Pulsed Eddy Current Testing (PECT) is an inspection technique used for corrosion under insulation (CUI) screening on carbon steel structures such as pipes, vessels, tanks and spherical tank legs without the need for contact with the steel surface.

The major disadvantage of a locomotive pod is that if the pipeline has concrete weight coating, the concrete around the sections to be clamped-on must be removed, this can add additional cost and difficulty to the operations, and also explains why as little as possible areas are needed for clamping.

Non-locomotive Non-locomotive pods lack integrated motors, hence, they are deployed, moved and retrieved by the ROV. An example of this is the Magna Scan. It is a versatile screening tool that uses electromagnetic acoustic transducers (UT) to assess the integrity of pipes, jumpers, flowlines and risers at a high rate of speed without disrupting production. It inspects volumetrically 360° around the pipe with an ROV and provides real-time data on the wall condition with a single deployment. The Magna Scan is a versatile screening tool that uses electromagnetic acoustic transducers to assess equipment integrity (e.g. pipe, plate, jumpers, flowlines and risers) at a high rate of speed without disrupting production. It inspects volumetrically 360° around the pipe with an ROV and provides real-time data of the wall condition with a single deployment. The Magna Scan also won the 2015 OTC spotlight on new technology award. This system provides numerous advantages compared to traditional subsea inspection methods. It identifies localised defects and general wall loss by optimising ultrasonic techniques. By combining Oceaneering's automated scanner, known as the Sea Turtle, with proprietary ultrasonic sensors, the system is capable of detecting internal and external damage mechanisms including corrosion, isolated pitting, cracking and other potential anomalies. This innovative system only requires clean surface access from the top portion of subsea assets (ZHANG et al., 2019)

Figure 15: (a) system components including sea turtle scanner, a subsea electronic pod, an ROV umbilical (b) sea turtle scanner providing 360 degrees coverage from the top of the pipe

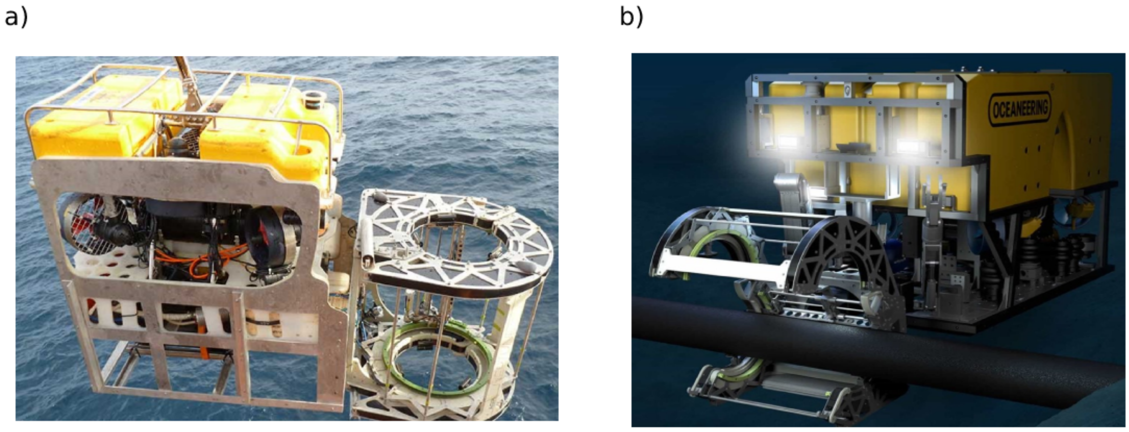


Source: Zhang et al. (2019)

Neptune is a high-resolution ultrasonic testing tool designed and developed to examine welds, subsea pipelines, risers, and tubular structures. Neptune's ROV-deployed technologies enable routine and project-specific ultrasonic inspection and provide cost-saving opportunities through reduced inspection time and reduced operational costs. Neptune performs high-resolution wall thickness mapping, time-of-flight diffraction (ToFD), and phased array weld inspection using multi-element, depth-rated transducers. The hardware and software developed in-house allow real-time data to be transferred topside via an ROV umbilical. Neptune's design provides operators with an alternative to traditional inspection methods. The neutrally-buoyant Neptune system is deployed via an inspection or work class ROV and delivers high-quality, automated inspection data and imaging. Using this data, operators can complete fracture mechanic analysis and assess the remaining life of subsea assets. The Neptune system can be provided with an ROV or as a stand-alone inspection solution capable of interfacing with the customer's ROV.

Tracerco subsea Computed Tomography (CT) scanner is useful in scanning coated

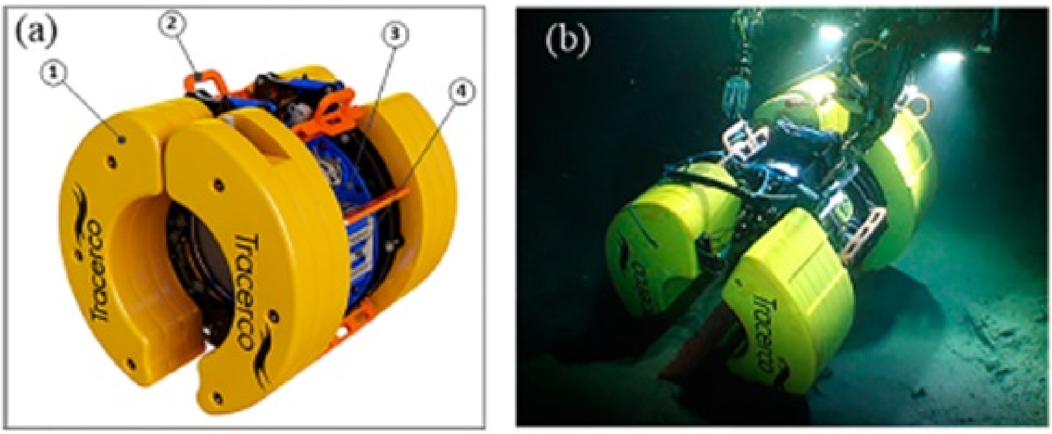
Figure 16: ROV tugging a) Flexlife riser monitoring tool (TENDERS, 2020) b) Neptune ROV based ultrasonic imaging tool



Source: Oceaneering (2020)

subsea pipelines by building the image from the outside providing high-resolution data. It is a very useful tool to use on unpiggable or difficult pipelines without disrupting production

Figure 17: Tracerco subsea Computed Tomography (CT) scanner Tracerco Discovery and its inspection applications: (a) discovery structure: 1. support frame, 2. ROV arms, 3. scan system, and 4. computer system; (b) inspection of subsea pipeline with the help of ROV.



Source: Zhang et al. (2019)

4.1.5 Non-Contact NDT Techniques

Non-contact inspections are visual inspections that may be carried out using Observational ROVs, Work Class ROVs and Autonomous Systems & Divers, utilising advanced cameras, lighting, Sonar and lasers. Visual testing is the oldest most common and one of the most important pieces of equipment on the ROV. It allows for the grasp of the environment around the vehicle. It is also one of the most common NDT techniques and by far the cheapest and most reliable techniques of all the other NDT techniques; it is conducted by the use of an ROV camera to detect defects with the eye via video feedback. Some ROVs have several cameras installed on them to allow the viewing of a wide range of angles, an example is the “KAIKO Mk-IV” where up to nine cameras were installed (NAKAJOH et al., 2016).

When there is a removal of marine growths to expose the structure and an inspection is carried out it is known as a detailed visual inspection. Weld damage and corrosion can be visible when this operation is carried out. Sometimes some difficult corners and points need to be inspected which the ROV camera cannot access, in this case, a borescope is used, it is a modern type of visual testing in remote visual inspections.

Microphone arrays that collect sound sources and characterize known as acoustic cameras are also used with ROVs, they can be used along with scanning sonar to battle water turbidity (MATSUMOTO et al., 2015), the images that are produced by each of the cameras facing the same direction is different, the optical camera image of a long iron drum can only be seen from the side it is facing while the acoustic camera facing thesame side can capture the top view even though the cameras were facing the same direction.

visibility can be a challenge underwater because of the Water turbidity which can sometimes block visibility (LILLO et al., 2016). Hence, there is a need for 2d or 3D imaging to mitigate this challenge which is why acoustic sensors are generally used.

Safe operations require visual computing technology such as 3D reconstruction and object detection. 3D data is a prerequisite to enable autonomous inspection of subsea installations with ROVs. Sonars are traditionally used for 3D data on moving platforms subsea but several approaches for underwater optical 3D imaging have been proposed over the years, a historical and detailed review of underwater visual techniques has been provided in Kocak and Caimi (2005). Light Detection and Ranging (LiDAR), is a comparatively new technology that can provide 3D with high-depth precision but is not suitable for moving vehicles.

5 ANALYSIS OF TRENDS AND EMERGING TECHNOLOGIES

ROVs are utilised both in the exploration and production phase of project development. During the production phase, inspections are performed on offshore assets throughout the life of the asset offshore. Fatigues, corrosion and collision on subsea structures and equipment are caused by the hostile sea environment. To guard the subsea structures and equipment against these defects, they must be detected and prevented at an early stage (SCHJØLBERG et al., 2016). Some of the regular inspections performed by ROVs are gas sampling, valve opening and closing, meter readings, leakage and fire inspection. The ROV carries multiple IMR sensors for inspection and manipulation (SHUKLA; KARKI, 2016).

Inspections account for the health of subsea structures and the condition of jumpers, umbilicals, connections, anodes and ancillary structures such as valve skids. The inspections reveal insights associated with third-party interactions such as trawling-induced “strikes”, boulder migrations, unintended anchor contacts and dropped objects. It involves using a camera for visual inspection and Non-Destructive Testing (NDT) on the various structures to check for their safety, security and integrity (BRITTON; TAYLOR, 2017). Every two to three years, inspections should be performed, this becomes very expensive which is why ROVs are used to reduce such large expenses (GINTAUTAS; SØRENSEN, 2018).

Visual inspection is the most basic form ROV inspection, it is simply using the ROV visual camera to see and inspect the structure or equipment. It is generally executed in three levels: Level 1 - General Visual Inspection (GVI), Level 2 - Detailed Visual Inspection (DVI) and Level 3 - Close Visual Inspection (CVI) (DALHATU et al., 2021). GVI only involves a visual camera to inspect the structures. DVI requires some cleaning to expose the body of the structure while CVI requires thorough cleaning to expose the surface of the structure to inspect any visible defects. Visual Inspections are part of a series of Non-Destructive Testing (NDT) that are employed in offshore structure inspections.

These are discussed in detail in the ROV inspection techniques section.

ROV inspections are an ever-evolving landscape of methods and techniques. Scientists, researchers and companies are finding new ways to inspect, quantify and record data subsea. In this section, we will discuss the most prominent methods and techniques involved in the inspection of offshore oil and gas structures which are carried out throughout the faces of project development of an oil and gas field. This chapter will discuss the established inspection techniques and methods of executing these tasks.

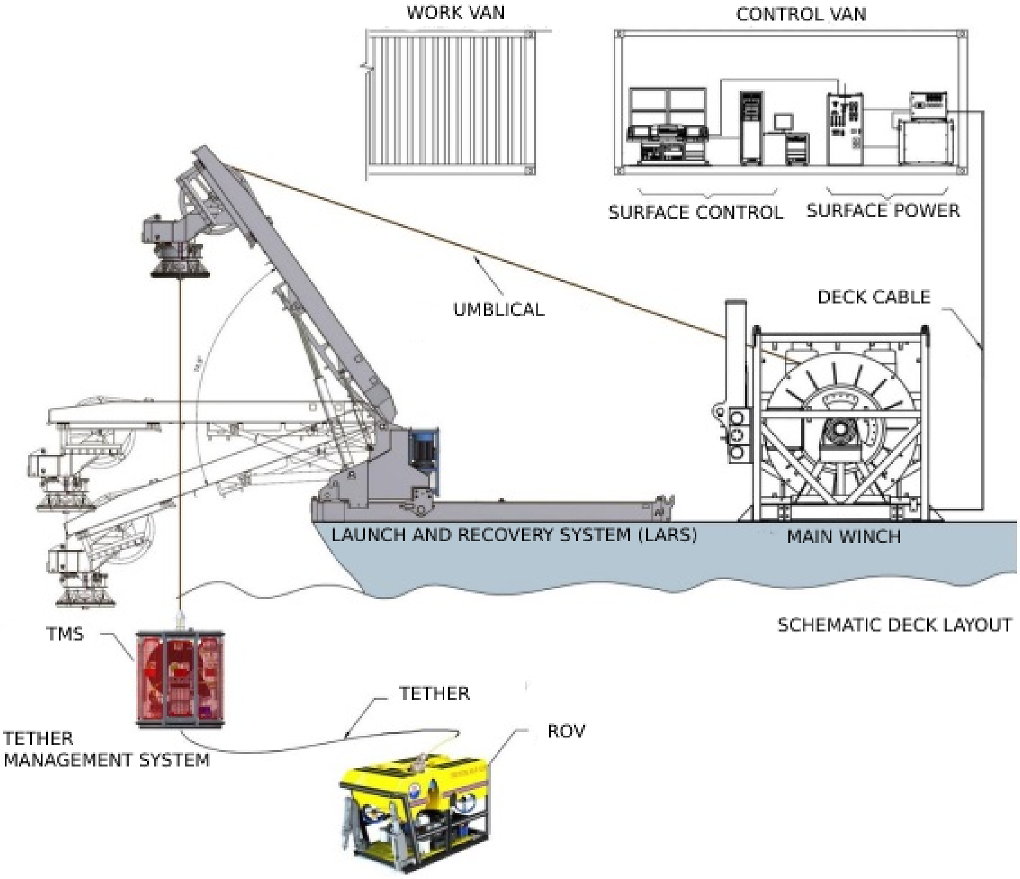
5.1 Conventional IMR method

Offshore asset inspections are part of the IMR operations, inspections operations cannot be fully understood without first understanding IMR operations and its process. The inspection process is usually subcontracted to surveyors who utilize ROVs to capture data from various integrated sensors/instruments which are subsequently reviewed and interpreted by human operators (STAMOULAKATOS et al., 2020). Because of the high operating cost and high system complexity associated with work-class ROVs, mini-ROVs that can be deployed and recovered by hand or with a small davit have been widely considered for subsea inspection and light-intervention applications. ExxonMobil has successfully used mini-ROVs to inspect floating structure hulls, mooring chains, and more (JABARI; CHENG, 2020). For these inspections, the mini-ROV is typically outfitted with a camera, cleaning apparatus, real-time video enhancement technology, callipers, and additional sensors. But for a sophisticated inspection, a standard IMR process must be carried out.

IMR (also referred to as IRM) is a term used for subsea intervention operations and its objective is to facilitate safe and cost-efficient inspection and intervention on subsea installations to maintain a sustainable operation of offshore assets. It is an industry driven by the need to keep costs low, spread financial and operational risk and create effective ways for making new technologies available (JOHANNESSEN; JONASSEN, 2018). IMR operations used to be executed from floaters and modified supply vessels, but from 2008 to 2009 purpose-built vessels like the Subsea 7 began to emerge (JOHANNESSEN; JONASSEN, 2018) with the traditional IMR setup equipment already installed. It consists of an ROV, a control command cabin or control room, a Launch and Recovery System (LARS), a Tether Management System (TMS) and other options like Object Recovery System (ORS), see Fig. 18.

There are different possibilities for how the vehicle is launched as can be seen in Fig. 19. 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 (MHS) is fastened to the templates on the seabed and is used to retrieve and lower components to the seabed template. In the following sections, we review the IMR operations process and the emerging methods of IMR.

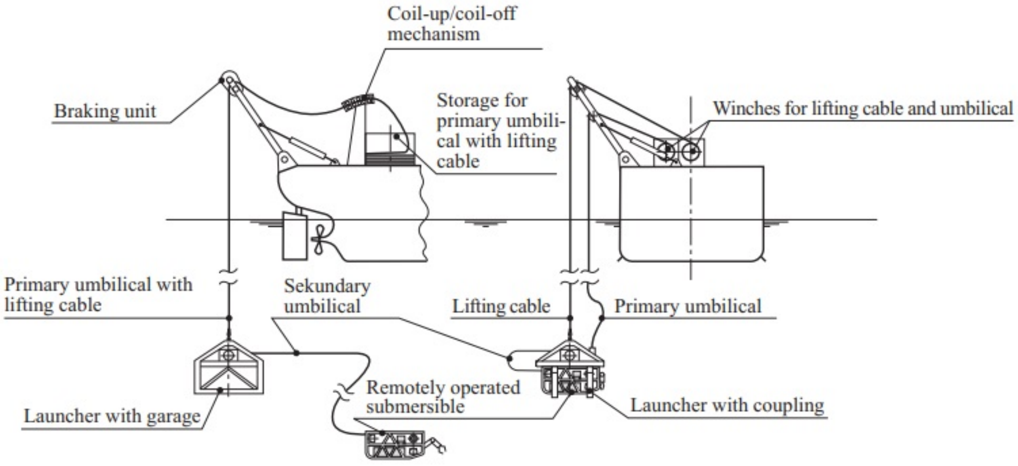
Figure 18: Traditional IMR Operation Setup



Source: EXPEDITION (2020)

IMR operations are carried out by hired subsea contractors who then hire a specialized vessel with the crew from the vessel owner or the shipping company. For major operators, mostly, vessels are hired on long-term contracts (JOHANNESSEN; MCARTHUR; JONASSEN, 2011), usually all year round. Minor operators hire vessels on shorter leases. A single IMR vessel may have up to 70 people on board belonging to up to five different companies (JOHANNESSEN; MCARTHUR; JONASSEN, 2015). From the point where

Figure 19: Possibilities for the application of a launcher for non-autonomous submersibles (ROV)



Source: GL (2021)

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 (ENGLAND, 1978). Therefore the subsea contractor is not only involved with the IMR operations but in other areas that include:

1. Exploration and Production (E& P)
2. Piper route surveying
3. Provision of subsea facilities
4. Decommissioning

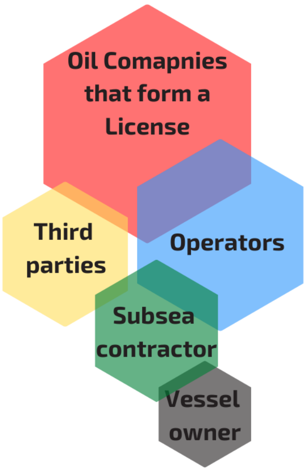
The oil company operating the field does not make independent decisions, it is the “license consortium” that assesses their needs and commissions the work that they want through the company operating the field. Then the IMR operations department groups the IMR operations into tasks known as campaigns (JOHANNESSEN; MCARTHUR; JONASSEN, 2015). 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 creates more specific plans known as the task plan. More than one task is usually carried out during the operation. The task plan is the document the crew executing the operation is directly involved with. It contains a to-do list of items covering checks, permits and a detailed description of the sequence and each physical step. For an operational example see each physical step in the following:

1. Run bilge keel or keel
2. Inspect running gear to stuffing block
3. Inspect sea chest(s)
4. Inspect secondary thrusters (bow and laterals)
5. Inspect through-hull fittings
6. Inspect bulkhead/pilings
7. Run anchor chain
8. Acoustically/visually search the bottom under the vessel

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 procedure. 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 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 (JOHANNESSEN; JONASSEN, 2018).

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 specialised service suppliers known as third parties who may be present to join the Subsea Contractor on the vessel as a consequence of maintenance contracts for the equipment they supplied. The relationship between the parties can be seen in Fig. 20.

Figure 20: IMR relationship between concerned parties



Source: Dalhatu et al. (2023)

5.2 Emerging IMR methods

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 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 analyzes 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, there is little to no difference between remote piloting and operating the ROV from the service vessel (NEWELL, 2018). This is a viable option because a successful test of remote piloting a WCROV was carried out by Statoil in 2016 with a 100% success rate (OCEANEEERING, 2021). The emerging methods provided by companies and researchers around the world are:

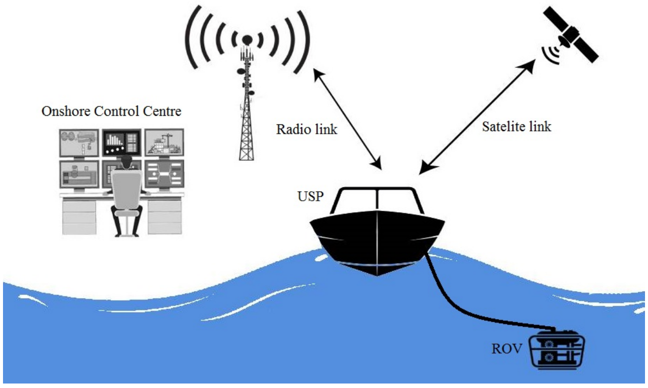
1. Unmanned Support Vehicle Platform (USP)
2. Resident ROV (RROV)
3. Semi-Resident ROV (S-RROV)
4. Drone ROV (DROV)

5.2.1 Unmanned Support Platform (USP)

Currently, this method utilises small Unmanned Surface Vessel (USV) or Autonomous Surface Vessel (ASV) as a carrier to transport, and provide communication, power, launch and recovery for an ROV, see Fig. 21 and 22. This reduces cost by avoiding the need for asset owners to keep a Field Support Vessel (FSV) on permanent hire. Companies are still working on full-size autonomous vessels which are to be expected by 2025 (VAGALE et al., 2021; PRIMEAU, 2019), British Petroleum (BP) has also publicly stated that 100 per cent of subsea inspections will be conducted by Maritime Autonomous Ships (MAS) from 2025 (PRIMEAU, 2019). 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 (FELSKI; ZWOLAK, 2020) which can be explained by the vague and unclear boundaries between the levels of autonomy, but there has been an attempt at harmonising and complementing these terms by Vagale et al. (2021). Noticing the ambiguity and lack of uniformity in the literature regarding this method, we aim to classify the methods that utilise an unmanned vehicle along with an ROV as an Unmanned Support Vessel Platform (USP).

Currently, these vehicles can be considered both autonomous (having levels of autonomy) and remotely operated vehicles. Several levels of autonomy tables were provided, among which were that provided: Maritime Autonomous Surface Ships (MASS) UK code of practice, Llyod's register in the document cyber-enabled ships and the International Maritime Organisation (IMO).

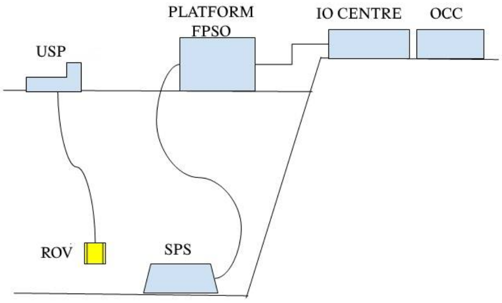
Figure 21: Unmanned Support Platform (USP)



Source: Dalhatu et al. (2023)

An Input-Output (IO) center is a facility that manages the input and output signals of ROVs, enabling operators to monitor and interact with the underwater environment

Figure 22: An illustration of Unmanned Support Platform (USP)inspecting the Subsea Production System (SPS) that is connected to the Floating Production Storage and Offloading (FPSO) that is connected to the Onshore Control Centre (OCC)



Source: Dalhatu et al. (2023)

through sensors, cameras, and manipulator arms. An Offshore Control Center (OCC) is a centralized command hub located onshore, from which skilled technicians remotely operate and control ROVs. OCCs use advanced communication systems to monitor and control ROV movements, collect data, and carry out inspection or intervention tasks without being physically present at the offshore site.

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 (FAHRNI et al., 2018). 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. One such limitation relates to the handling capacity of the autonomous LARS, which determines the maximum allowable weight of the ROV and tether. Consequently, this imposes restrictions on the operating depth of the ROV and the range of tooling capabilities that can be accommodated during the operation

This type of setting utilizes line-of-sight communications that are 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. The latency effect in a this system refers to the delay between operator commands and the ROV's response. It can arise from communication delays, processing time, and system response time. Higher latency can impact control responsiveness, stability, safety, and task execution. To mitigate latency, optimization of communication channels and control systems, predictive control algorithms, and operator training can be employed. By minimizing latency, operators can achieve better control, safety, and efficiency in carrying out tasks underwater.

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 (PRIMEAU, 2019). Automated tether management systems are used to mitigate this risk (FAHRNI et al., 2018).

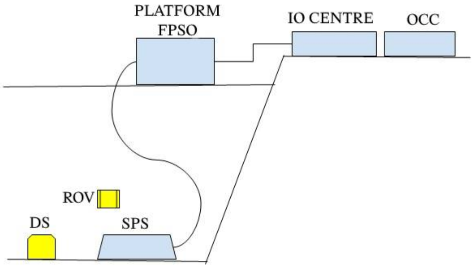
A good communication link ensures little to no difference between remote piloting a USP and operating the ROV from the service vessel. Several USP combination systems are emerging, such as the Hushcraft Sea-Kit system that has plans to develop an integrated ROV solution and others like L3ASV with their tested ROV prototype as well as several specialist systems from tier 1 contractors such as Subsea-7, Oceaneering, IKM Subsea, ECA Group, SAIPEM, to mention only a few (PRIMEAU, 2019).

5.2.2 Resident-ROV (RROV)

RROVs are permanent IMR installations offshore, Figure 23 shows a schematic of the RROV method. Its power, communication and TMS are all set up offshore, in different possible configurations of choice (TRSLIĆ et al., 2018) as shown in Fig. 24. They have the capability of a non-stop operation, for example, the Oceaneering's resident Freedom ROV has a Subsea Docking Station (SDS) with the capability of conducting a continuous underwater operation for the duration of 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 (NEWELL, 2018).

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 (STEVENS, 2019). 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 (LILJEBÄCK; MILLS, 2017). These types of rare ROVs fall under Class V. There is also a similar design by Sverdrup-Thygeson et al. (2017) called underwater swimming manipulator (USM) with supervised autonomy. Resident vehicles can perform a task that

Figure 23: An illustration of RROV method



Source: Dalhatu et al. (2023)

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 (NEWELL, 2018). But they are not without challenges, 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. (2015) presented an application of fuzzy logic for a safe autonomous IMR operation using visual-based pose estimation techniques and Tang et al. (2017) also presented a vision system localization system that is capable of eliminating drift error using fuzzy inference.

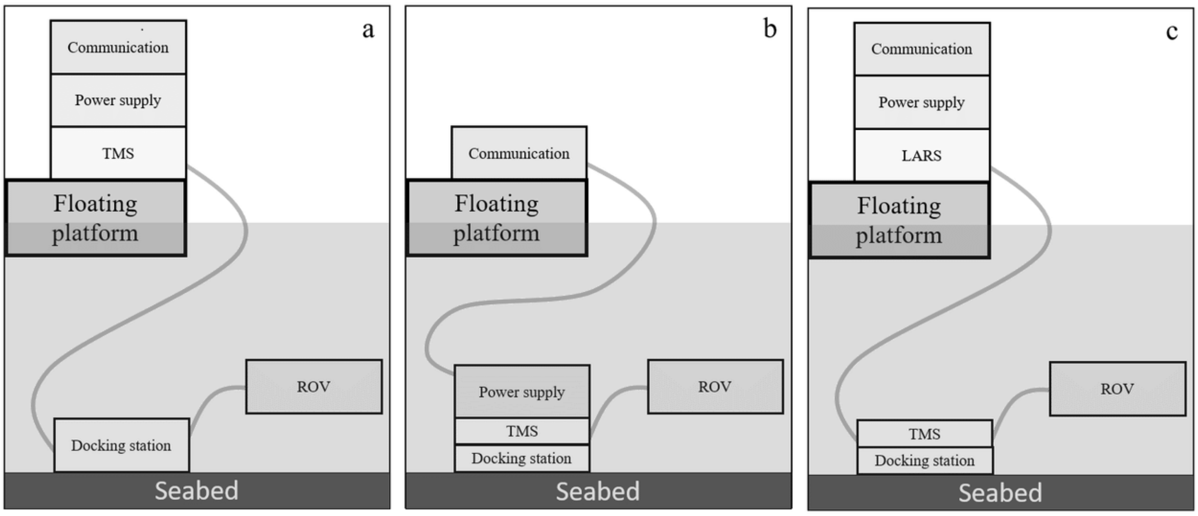
RROV concept is a new level of asset management. It is an important part of the development of future subsea factory concepts and/or in inhospitable geographical areas like the arctic regions.

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.

5.2.3 Semi-Resident ROV (S-RROV)

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 25 shows a basic schematic of this SRROV method. It is a temporary instalment that serves the purpose of an RROV. A

Figure 24: Resident ROV system configuration

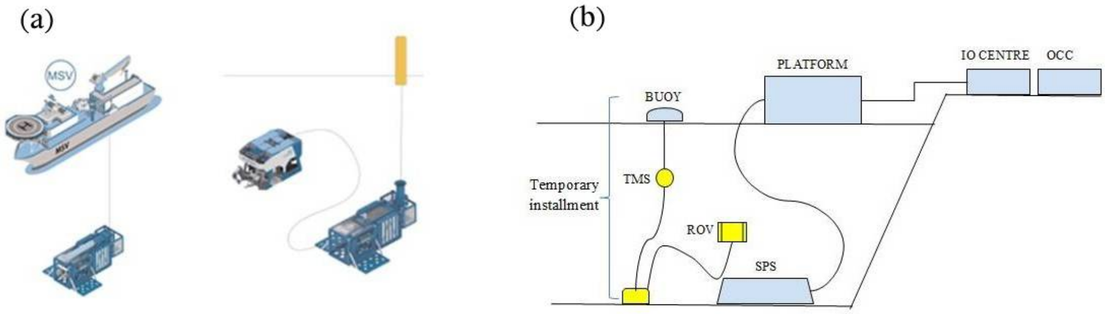


Source: Trslić et al. (2018)

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. 25b. But an Enhanced ROV (E-ROV) is used in place of a traditional ROV.

The E-ROV is a battery-powered WCROV with a complete 4G LITE buoy and it is controlled from onshore with a battery capacity of 24hrs. Since wireless communication underwater is still a challenge, the best option currently is by the use of 4G buoy (STEVENS, 2019). The buoy also provides power to the subsea hanger through the mooring system. Monthly visits are carried out to recharge batteries and provide needed additional toolings. This approach reduces the dependency of vessels on site hence reducing cost (STEVENS, 2019).

Figure 25: Semi RROV deployment and operational modes



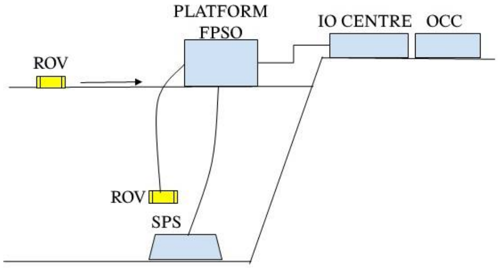
Source: Stevens (2019), Dalhatu et al. (2023)

An important factor in semi-resident ROV is good communication. There is a widespread quality 4G network in the North sea that allow for ROVs to be flown remotely (STEVENS, 2019).

5.2.4 Drone ROV (DROV)

In the past and even in the present some use the term drone to refer to ROVs (HANSEN; BENDER, 1996; BUTCHER et al., 2021; LIMA et al., 2021), but we find the term rarely correctly applied. It is relatively the same as the misnomer: drone ships, a colloquial term. The word drone is an aviation term for unpiloted aircraft or spacecraft, UAVs 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 Figure 26). In reality, we find that ROVs are transported to the site and launched from a vessel or platform at the site. In more complex operations, a large vessel is used with large crews on deck to perform the ROV operations on site. But an argument could be made that Hybrid RROVs could be seen as drones, however, these vehicles operate within the vicinity of the structures but this could change in the future when RROVs are utilised by hiring to nearby offshore instalments to reduce idle time and generate revenue, this will require an unprecedented shift in IMR operations. Nonetheless, drone technology in ROV operation is yet to be fully developed, there have been projects by researchers and prototypes. In 2017, Wright (2017) 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 Wright and Chan (2019), trials were undertaken in the arctic to investigate its sustainability for polar operation and to determine any necessary modifications.

Figure 26: An illustration of DROV method



Source: Dalhatu et al. (2023)

In May 2018, Houston Mechatronics Inc. introduced an ingenious innovation called the Aquanaut robot (see Figure 9). 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 travelling 200km to conduct offshore typical tasks. It has the capabilities of an AUV and ROV (Hybrid-ROV) and can switch to any depending upon the requirement. It can travel in a submarine mode to the site where it can transform its body to a more square block traditional shape of ROVs revealing its linear actuators, arms and additional thrusters (MANLEY et al., 2018).

5.3 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 imperative 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 on-board ROV maintenance capability, nonetheless a faster and cheaper method than the traditional method. Currently, the S-RROV 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 a slower response time compared to an already installed S-RROV or RROV. However, DROVs can be used as S-RROVs 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 cheaper over the long run. See the comparison of the methods in Table 1.

Table 1: Comparison of methods

Method	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, it may also lead to some passerby picking up the vessel and 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**: (1) Faster than the traditional method (2) Cheap (3) No need for new equipment **Cons:** (1) Technical capabilities limitation (2) No spare ROV (3) Theft/Piracy
S-RROV	Fast response time when it has already been situated at the site but is slow if it has been decommissioned and has to be set up again, capability to harbour 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**: (1) Fast response when already installed (2) Enough tooling (3) Sufficient technical capabilities **Cons:** (1) Expensive (2) No spare ROV (3) 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 for theft or tampering by a curious passerby. There might however be a challenge with cybersecurity 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:** (1) Fast response (2) Enough tooling (3) Sufficient technical capabilities (4) No Theft/Piracy **Cons:** (1) Expensive capital investment (2) New installments of subsea infrastructure (3) 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 for 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:** (1) Cheap (2) No need of new equipment installations (3) Faster than the traditional method **Cons:** (1) Slow response (2) Limited tooling (3) Possible loss of vehicle

6 CONCLUSION

The offshore inspection industry still relies heavily on traditional methods, and the full adoption of new approaches for IMR operations is hindered by technical and operational challenges. The Resident ROV (RROV) method is currently the most reliable for offshore inspections, but there is a potential for RROVs to be utilized as Sea Drones, traveling to different offshore asset locations to perform operations and generate revenue, thus addressing the issue of idle time and maximizing the investment capital. The classification of ROVs presents challenges due to the transitional nature of parameters and modes of operation, requiring a more stable taxonomy for vehicle selection. Emerging methods such as Unmanned Support Vehicle Platforms (USP), Semi-Resident ROVs (S-RROV), and Drone ROVs (DROV) offer alternatives, but the RROV method remains the most efficient and reliable for offshore IMR operations, especially when combined with DROVs.

The future vision involves Drone RROVs and tools placed within offshore assets, enabling remote assistance, monitoring, and aligning with the industry 4.0 framework. Inspection techniques employ various tools and technologies, with Ultrasonic Testing (UT), Alternating Current Field Measurement (ACFM), and Eddy Current Testing (ECT) standing out for their performance and cost savings. The future of ROV-based IMR operations holds the potential for revolutionary changes, with the possibility of inspections conducted without vessels, using ROV drones and offering opportunities for scientific studies and underwater observations.

This research was conducted in two parts. The first part reviewed the scientific literature on ROVs application in the oil and gas industry to provide a decent scope of ROVs and the challenges faced. Three results were obtained from this part:

1. There is yet to be a substitution for the conventional method of performing IMR
2. It highlights the benefit of developing a single vehicle that can perform IMR tasks.
3. As the demand for ROVs continues to rise there will be new requirements which will shape the evolution of ROVs

Based on the result and conclusion of the first part, the second part was written. The second part evaluated the potential substitutes of the conventional IMR method that are emerging, the methods were categorized into four, based on the configuration of the ROV system and the technology used. The evolution of ROVs has led to a lack of a widely accepted classification for ROVs. Classifications, in general, were defined by grouping ROV functions and capabilities needed for generalized scenarios. The classification also placed too much attention on the mode of communication and operation and implied that these are parameters for classification. This is not adequate to capture the multifaceted nature of ROVs. 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 the second part presented a new taxonomy to fill this need. The second part has produced the following results:

1. A new ROV classification that is sustainable with technological developments.
2. The DROV method is a developing technology that can serve as a single vehicle that can be utilised to perform IMR tasks without the need for support vessels, thereby reducing cost and increasing effciency.
3. RROV is the most efficient and the most 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.

ROV technology is in rapid development, hence new ROV technologies are constantly emerging with new methods of conducting subsea inspections; USP, RROV, S-RROV and DROV for the purpose of cost reduction, along with the development of new tools; locomotive and non-locomotive, and inspection techniques; MEC, PEC, CT for increasing efficiency and reduction of offshore asset failure rate. The rapid advancement and the changing nature of ROV technology have contributed to current difficulties in ROV classification and unmanned underwater vehicles at large which this research made an attempt in providing a more reliable classification.

Based on this extensive research, the foreseen future of IMR operations leans towards smart services of industry 4.0 through utilising DROVs and RROVs setups. The combination of these will be the most efficient method of inspecting offshore assets, ensuring their health and uninterrupted operation.

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