OT5301 CA: Mini-Research on Subsea Well Intervention Technology – a Brief Review

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Abstract

The seafloor is a space full of resources, of which subsea wells are the most important way to access them. Subsea well intervention refers to a set of specialized techniques and operations performed on underwater oil and gas wells to enhance their performance, extend their lifespan, or address specific challenges. Traditional intervention equipment includes drilling rig and hard riser. In this CA paper, traditional subsea well intervention technology is briefly introduced and categorized. Its working principle and process are also briefly discussed. Nowadays, more intervention platforms and tools are developed to provide faster response, higher efficiency, and more flexible operation. Especially with the development of artificial intelligence technology, robotics has been applied in subsea engineering. Autonomous robots, flexible robots are termed subsea well intervention, providing better performance. As the foundation of the industry, many companies have also offered their products to better address the challenges that may be encountered during subsea well interventions. This CA paper also provides a brief listing and introduction of the outstanding ones among them, together comes with their key products for subsea well intervention.

Keywords. Subsea System, Intervention, Subsea Well, Maintenance.

1. Introduction

1.1 Background and Purposes

The seabed is a wet, saline, dynamic water body. It is a “hotbed” for corrosion due to the combined effects of salinity, oxygen, and moisture on metal surfaces [1]. This accelerates electrochemical reactions, leading to rapid degradation of materials. The presence of salts in seawater enhances conductivity, making electrochemical cells on metal surfaces more active and promoting the anodic and cathodic reactions. This accelerates the loss of electrons from the metal, exacerbating corrosion. Additionally, the presence of microorganisms in the seabed can intensify corrosion as they produce corrosive substances or directly participate in the metal degradation process. Consequently, the corrosive effects in the moist environment of the ocean floor are significant and complex, necessitating effective protective measures to extend the lifespan of metal materials. In addition, studies have shown that the corrosive effects of seawater are particularly pronounced for fasteners [2]. Traditional protection methods include methods such as anodic protection with sacrificial cathodes, however, this protective material also needs to be replaced on a regular basis, which means that regular maintenance is even more essential.

On the other hand, the seabed is filled with reefs, seaweed, moving mud and pebbles. They pose significant threats to subsea well equipment. The impacts of gravel can lead to deformation and leakage of various cylinder bodies, or even sever transportation pipelines. This not only causes equipment to malfunction but can also trigger leak events, damaging the marine ecosystem. Additionally, seaweed and debris easily damage dynamic equipment (such as subsea motors), rendering them inoperative. These power source equipment are particularly challenging to replace, posing challenges for subsea intervention.

What's more, when a well comes to the end of its life cycle, it will be difficult for it to be economically satisfactory and there are safety issues. These wells need to be abandoned in a safe and efficient way.

Although, as previously mentioned, there are various resources and opportunities at the seabed, the equipment located there is not always safe. This means that compared to equipment installed on land, subsea equipment is at higher risk. Naturally, they also require more frequent, complex inspections, maintenance, and repairs. Additionally, the complexity of the underwater environment necessitates the use of specialized equipment for maintenance that differs from that used on land. Therefore, subsea intervention has emerged. Early to the year of 1998, subsea intervention technology has been proposed [3]. **Fig. 1** shows the first subsea intervention platform in 1998, which is a diver/diverless support vessel, modified for intervention purposes (especially for the subsea wireline systems).

Fig. 1. Diver/diverless support vessel for the intervention operations.

Subsea intervention often refers to the collective term for equipment, technologies, and methods used in subsea engineering, aimed at providing low-cost, high-efficiency, and rapid response maintenance, repair, and rescue operations [1]. This is very crucial in the challenging and complex environment in the deep water, where the integrity and functionality of subsea infrastructure are vital for the success of various industries, including oil and gas extraction, telecommunications, and renewable energy. In 2023 (the author of CA paper did not find the data for 2024), the total market for subsea intervention comes to USD 4.08 billion [4].

Among different objects, subsea well intervention refers to various maintenance and repair operations conducted in underwater oil and gas wells. These operations typically take place near the wellhead but do not require lifting the equipment at the wellhead to the sea surface. Subsea well intervention is used to address various issues such as wellbore blockages, subsea equipment failures, production enhancement, and altering wellbore fluid properties.

Currently, the most common subsea well intervention system consists of a carrier and a toolset that are combined to accomplish the dive, movement, and given intervention elements of the operation. The carriers could be operated vehicles (ROVs), subsea robots, intervention vessels, and riser systems. Their different sizes (from hundreds of meters to tens of centimetres) determine their different functions. Of course, in engineering, they often work together to accomplish a specific goal. Tools are designed and installed according to specific engineering objectives. Some of them can be used for injecting chemicals, some for replacing fasteners, and some for disassembling equipment, etc.

In addition, expanding the application scenarios (in other words, collecting objectives) of existing subsea wells (update), scrapping and decommissioning are also considered by some to be the scope of subsea well intervention. They will also be further described in the below sections.

1.2 Classifications

Light Intervention. Light interventions are the least invasive and typically involve wireline or slickline operations. These operations are conducted through the existing riser and wellhead systems, requiring minimal additional equipment. The primary objectives of light interventions include routine maintenance, such as replacing valves or gauges, and diagnostic tasks like logging or sampling. Light interventions are cost-effective and have a relatively low impact on the environment. However, their scope is limited to tasks that can be performed through the existing wellbore without the need for heavy equipment or significant modifications to the well infrastructure.

Medium Intervention. Medium interventions are more complex than light interventions and often involve the use of coiled tubing. Coiled tubing interventions allow for a greater range of operations, including scale removal, acid stimulation, and the deployment of downhole tools for repair or maintenance. Unlike light interventions, medium interventions may require temporary modifications to the wellhead or the installation of additional equipment to facilitate the coiled tubing operations. These interventions strike a balance between the minimal invasiveness of light interventions and the extensive capabilities of heavy interventions, making them suitable for tasks that require more than wireline capabilities but do not justify a full-scale workover. In fact, because medium intervention is a balance between the two (similar to "interpolation"), many scholars only categorize subsea well intervention as light intervention and heavy intervention. intervention. Even, IHS Markit categorizes all intervention units as light well intervention vessels, for which the author of this CA paper does not fully agree with. The correctness of the different categorizations is not to be discussed in this CA paper.

Heavy Intervention. Heavy interventions are the most invasive and involve significant alterations to the well structure or the use of a drilling rig. These operations may include side-tracking to create a new wellbore, performing major repairs or modifications to the wellhead and casing, or complete well abandonment. Heavy interventions are typically reserved for situations where the well's integrity is compromised, or substantial changes to the well's configuration are required. Due to their complexity and the need for specialized equipment, such as drilling rigs or workover units, heavy interventions are the most expensive and time-consuming type of subsea well intervention.

1.3 Challenges

Subsea well intervention presents several challenges due to the complex nature of underwater operations and the harsh environments encountered. The challenges are listed below (for engineering real cases, there are certainly more obstacles. Hereby, only the ones caused by subsea environment are listed).

Depth and Pressure. Subsea wells are often located at depths ranging from a few hundred to several thousand meters below the sea surface. At these depths, the ambient pressure can exceed several hundred atmospheres, and temperatures can drop significantly. These extreme conditions pose significant challenges for the materials and equipment used in well interventions. For example, seals and hydraulic systems must be designed to withstand high pressures, and the viscosity of fluids used in the operation may need to be adjusted to ensure proper flow characteristics. Additionally, the high pressure can complicate the control of well pressures and the management of potential blowouts.

Remote Operations. Conducting well interventions in subsea environments requires remote operation, typically using Remotely Operated Vehicles (ROVs) or automated systems controlled from surface vessels or platforms. The reliance on remote technologies introduces challenges in terms of the precision and reliability of operations. ROVs and other robotic systems must be equipped with specialized tools and sensors to perform tasks such as manipulating valves, conducting inspections, and delivering materials to the well site. The limitations in dexterity and feedback compared to human operators can make complex tasks more challenging and time-consuming.

Cost for Subsea. The financial investment required for subsea well interventions is significantly higher than for interventions in more accessible locations. The need for specialized vessels equipped with dynamic positioning systems, advanced ROVs, and other subsea equipment contributes to the high cost. Additionally, the operational expenses related to maintaining a presence in remote offshore locations, including logistics, crew support, and safety measures, add to the overall cost. These economic considerations can impact decision-making and prioritization of intervention activities.

Environmental Concerns. Subsea well interventions carry inherent risks to the marine environment. Any accidental release of hydrocarbons or other contaminants can have severe ecological impacts, particularly in sensitive or biodiverse areas. The deep-sea environment is less understood and more fragile than terrestrial ecosystems, and recovery from disturbances can be slow. Therefore, there is a heightened focus on risk management, spill prevention, and emergency response planning in subsea operations. Environmental regulations and standards are stringent, and operators must demonstrate a commitment to minimizing ecological impacts through careful planning and adherence to best practices.

Slowly-developing Market. The subsea oil and gas industry is currently experiencing an "flat phase". As a result, intervention has also been affected. However, as mentioned above, well intervention and plug and abandonment (P&A) operations are also an important part of subsea well intervention. And this part of the market is still growing to date [5]. On the other hand, the forecast report suggests that the offshore pipeline industry may be entering a new upswing that will last until at least 2029 [6]. Another report also gives its opinion on the potential increasing before 2029, not only focusing on the pipelines but the whole subsea engineering industry, especially intervention-related work, shown in **Fig. 2** [4]. Especially in Europe, more fields with complex extraction conditions are being further developed thanks to new technologies. Demand-driven is also another major reason.

To overcome these key problems in subsea well intervention, many new equipment (especially new subsea robots) and techniques are being emphasized and developed. These frontiers are summarized with examples in Section 4.

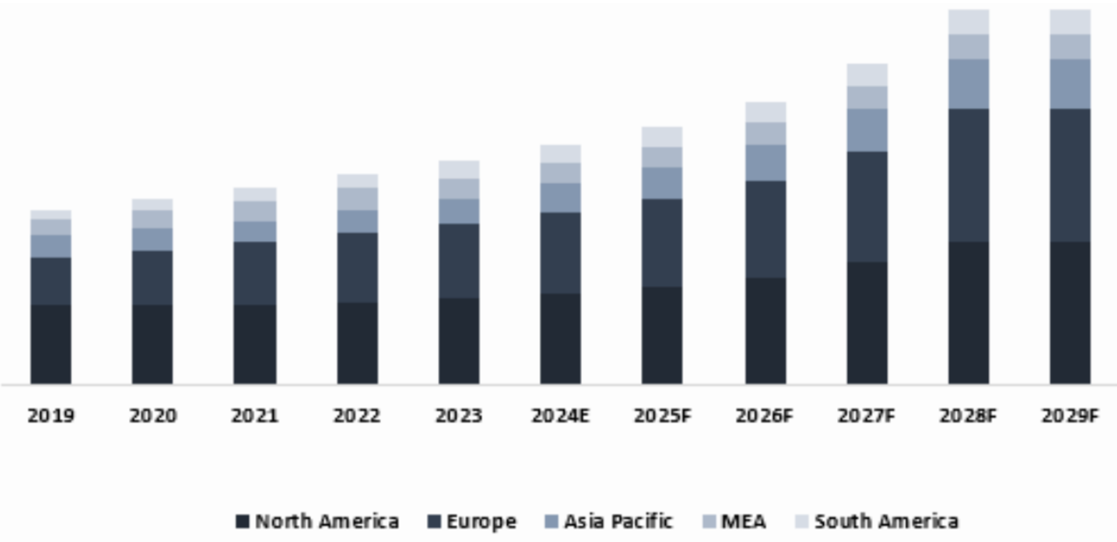

Fig. 2. Predicted global subsea intervention market (Market size by value, region. 2019 – 2029F) [4].

2. Equipment and Supports

During the subsea well intervention process, a series of specialized equipment is utilized. On one hand, large-scale platform equipment becomes akin to a "base," providing major support for the work. With their help, engineers are able to perform various types of interventions. These platforms primarily fall into two categories: rig-based intervention platforms and intervention vessels. Each has its own characteristics, which are introduced in this section.

2.1 Intervention Platforms

Rig-based Intervention Platforms.

Rig-based systems are currently the most common intervention platforms. Their primary characteristic is their sufficient stability (where intervention vessels perform poorly) and they offer powerful adaptability. Therefore, they can complete a variety of intervention tasks, including major repairs, plug and abandonment. From the perspective of the operational environment, they can work in deeper waters and are not afraid of certain levels of severe weather conditions. For example, if an intervention task requires the use of heavy-duty machinery, then a rig-based intervention platform must be selected. Clearly, stability plays an irreplaceable role here. On the other hand, they have more ample space to handle a higher workload and continuously complete intervention work without interruption.

Rig-based intervention platforms indeed possess limitations. Their manoeuvrability is relatively inferior, thereby impeding swift response to demands across various oilfields. Consequently, their primary deployment is concentrated around numerous subsea wells within a singular oilfield. Under such circumstances, the formidable operational single capacity of these platforms renders a substantial benefit.

Fig. 3. The OOS drilling-rig-based intervention platform.

Intervention Vessels.

Intervention vessels are vessels or platforms with subsea intervention capability and are considered to be the most important component of subsea intervention [7, 8]. They typically carry various equipment to perform specific operations such as well maintenance, repair, enhancement of production, and decommissioning. Another key feature is their mobility. Mounted on vessels, they can move between different wells and oilfields, improving efficiency and expanding their application scenarios. Most intervention vessels are optimized and specially designed for specific tasks or geographical conditions of the mission, allowing them to achieve their objectives in

Fig. 4. Design-stage illustration of a STXOSV Arctic intervention vessel [8].

harsh environments. A typical case is the All-Year Intervention Vessel for the Barents Sea [8], shown in **Fig. 4**. Due to its geographical location, this area is often covered by ice and snow. Ordinary intervention vessels struggle to reach the oilfields to perform operations. Therefore, specially designed intervention vessels will work together with icebreakers and rescue ships. As a fleet, they provide high stability and manoeuvrability in icy conditions. Although this specific vessel is still in the design phase, its significance is profound.

Additionally, they are usually equipped with a moon pool. In intervention vessels, a moon pool is a crucial feature that consists of a vertical opening through the vessel's hull, enabling the direct deployment and retrieval of subsea intervention tools and equipment from the deck to the water below. This design enhances operational safety, efficiency, and stability by providing a protected area that minimizes the effects of sea conditions on the equipment being deployed.

It is worth noting that, DNV GL classifies offshore drilling and support units based on a set of variables. The vessels commonly used for both intervention and plug and abandonment operations can be divided into three categories; Mobile offshore drilling unit (MODU), well intervention unit (WIU) type 1 and well intervention unit Type 2. This means that due to the versatility of the DRILLING UNIT, it is sometimes not positioned as an intervention-specific device, but as a general-purpose device.

Intervention Riser Systems (incl. Riserless)

Riser is referring to the “umbilical connection”, namely the connection between the platform and subsea well. An intervention riser is a specialized type of riser used for subsea intervention operations, such as well maintenance, repair, or installation of equipment. It provides a conduit between the surface vessel and the subsea wellhead or equipment, allowing tools and fluids to be safely deployed and retrieved. Intervention risers can be rigid or flexible, with the choice depending on factors like water depth, intervention requirements, and the type of intervention equipment being used. They are designed to withstand the harsh subsea environment and the mechanical loads imposed during intervention activities.

A common alternative to risers is riserless systems, also known as riserless technology [9]. It is primarily used for light well intervention. Riserless technology is a technique used in subsea intervention operations that does not involve the use of traditional risers, primarily operating directly from the sea surface to the subsea wells through special equipment and methods. This technology typically involves the use of Riserless Intervention Systems (RIS) [10] and Riserless Well Intervention Systems (RWIS) [11]. RIS usually consists of a set of subsea control modules and intervention tools that can be deployed and operated via subsea pipelines or remotely operated vehicles. RWIS, on the other hand, is a more complex system that may include a temporary intervention string and a subsea intervention device for conducting more complex downhole operations, such as plugging, testing, and sampling. Riserless technology reduces the complexity and cost of subsea operations, enhances operational flexibility and efficiency, and minimizes the impact on the marine environment. Although the tasks it can complete are currently quite limited, there is rapid growth (maybe similar to the reasons for the growth in vessels), so it could become a trend. **Fig. 5** shows a RIS system by Saipem America (early to 2006), which has the capacity to work in the ultra-deepwater at the depth of more than 10,000 ft. It uses a modular approach for installation of equipment, as well as the ability to disconnect from subsea equipment. As demand for ultra-deepwater continues to grow, RIS will also benefit. In addition, more companies are beginning to develop related new equipment, such as ultra-heavy ROVs, which are capable of controlling and operating RIS.

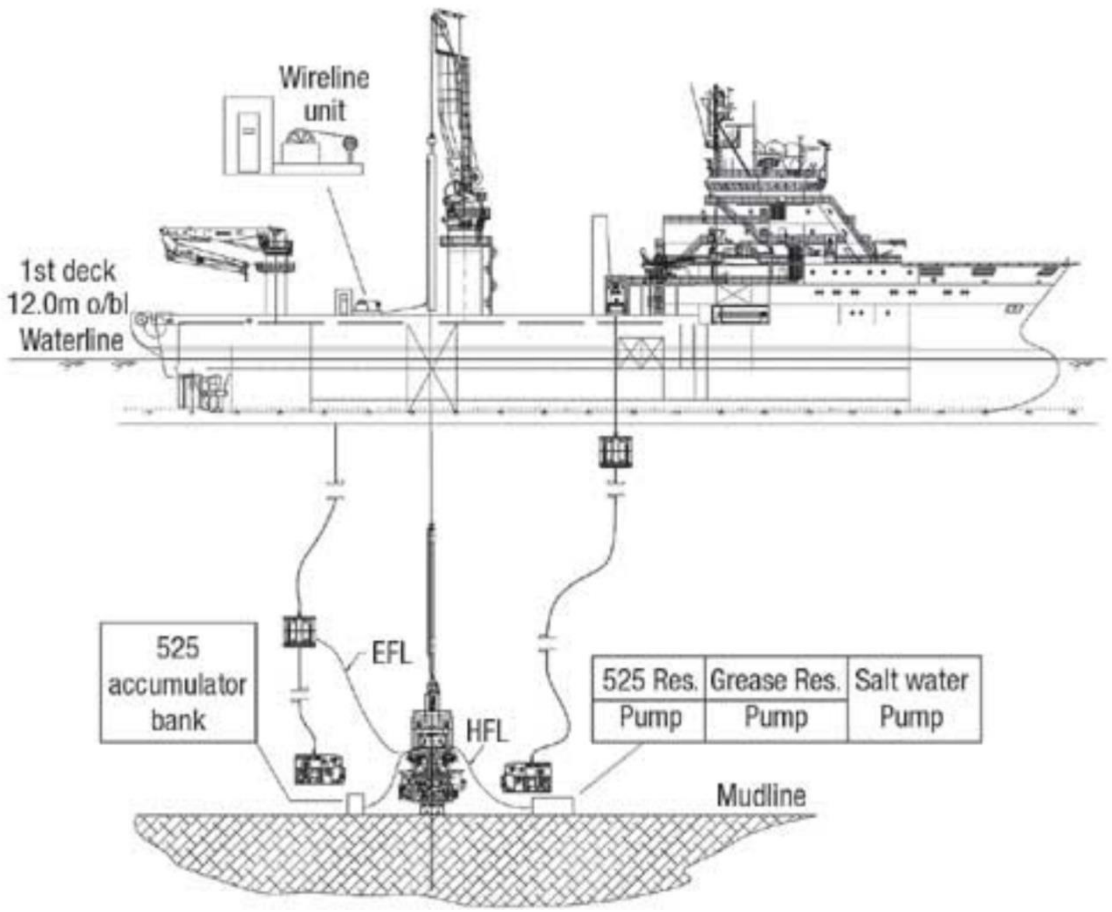

Fig. 5. A deepwater / ultra-deepwater RIS intended to perform wireline interventions in water as deep as 10,000 ft [12].

Section Conclusion

The manoeuvrability of intervention vessels comes at the cost of sacrificing individual (single-platform) performance. This implies that they are incapable of bearing the load of massive equipment, thereby limiting their application scope. In other words, rig-based platforms and intervention vessels constitute two complementary working platforms. Their collaboration ensures that both mobility and availability are adequately addressed.

Some researchers are holding the opinions that the future belongs to vessels, not the large-sized platforms [13]. the technology for subsea well intervention is constantly evolving, with miniaturization being one of the most critical aspects. This development allows an increasing number of tasks to be completed by smaller devices, which can evidently be integrated into intervention vessels, eliminating the need for a massive, redundant rig-based platform. Consequently, the rapid response characteristics of vessels are fully leveraged.

2.2 Intervention Agency (Underwater Vehicles)

In order to carry out mobile intervention operations underwater, underwater vehicles are very crucial. They can usually be divided into three categories: Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV), and Human Occupied Vehicles (HOV). These underwater robots are capable of performing maintenance and repair tasks in harsh deep-sea environments, ensuring the normal operation of subsea oil and gas wells.

Remotely Operated Vehicles (ROV).

ROVs are particularly widely used in subsea well intervention. They are remotely operated by personnel on the surface and can perform precise tasks such as opening and closing valves, installing and removing equipment, and conducting visual inspections. The use of ROVs significantly reduces the risk of direct human diving and allows for operations at extreme depths and pressures, making them an essential tool for subsea well intervention. One of the most notable features of ROVs is that they also have an umbilical cord connected to the mother platform like vessels. Through this umbilical, they can be better controlled and occasionally used for the transportation of materials. Therefore, their operations are more controlled. With the assistance of various sensors and operated by real humans, they are able to perform precise measurements and intervention work.

In addition, it has a very wide volume range, up to a size of about 3 meters. One example among them is Deep Discoverer (**Fig. 6**), developed in 2018. Capable of diving to depths of c.a. 3.7 miles (6,000 meters), Deep Discoverer provides unprecedented access to the deep ocean. Because of its huge size, it can be fitted with a very large number of sensors, providing excellent sensing capabilities. Another interesting thing is that videos of its work are being consistently streamed live on the internet. Unfortunately, it is currently under refurbishment and has not yet returned to the world of subsea [14].

The ROV system consists of surface and subsea components. The surface part includes the control unit (or pilot unit) and the Launch and Recovery System (LARS). The subsea part comprises the Tether Management System (TMS) and the ROV itself. Typical system structure is shown in **Fig. 7**.

Fig. 6. Deep Discoverer ROV [14].

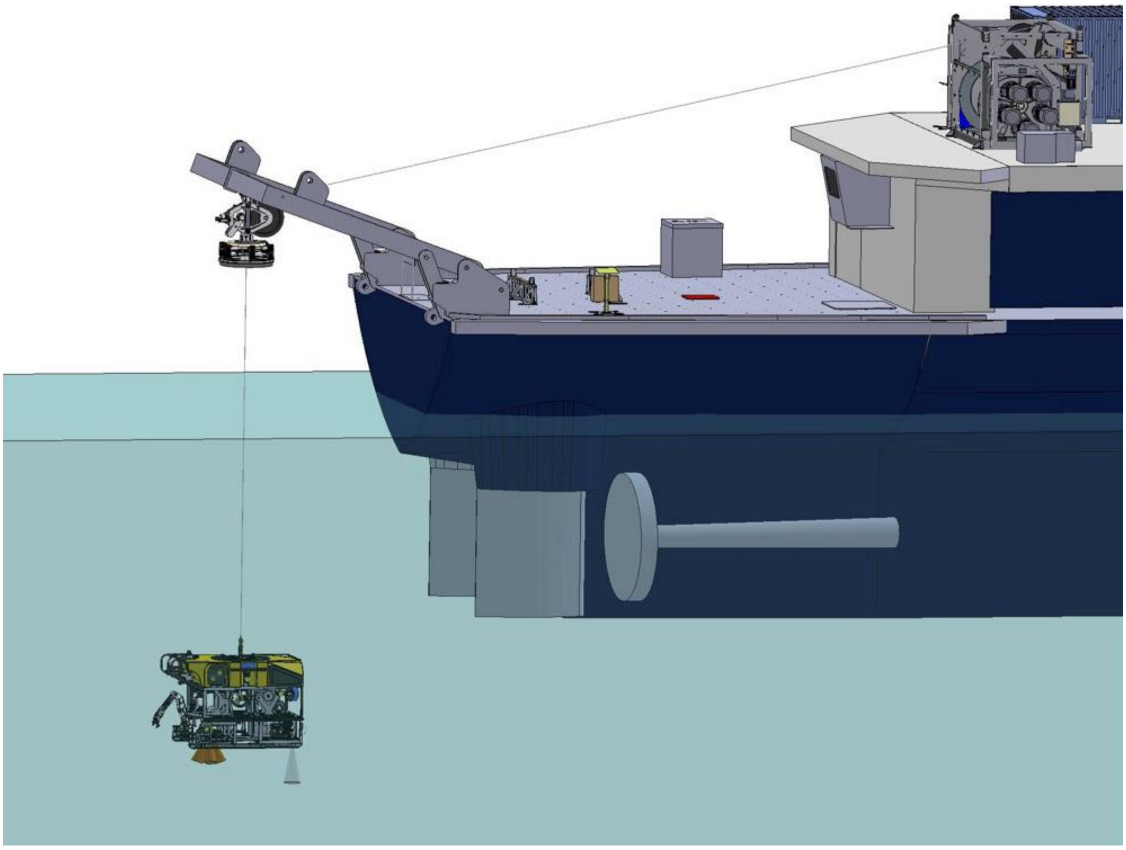

Fig. 7. A typical structure of ROV system [15].

Autonomous Underwater Vehicles (AUV). AUVs mainly contribute to the initial survey and monitoring in subsea well intervention. Shown in **Fig. 8**, the AUV has no cables connecting to the main platform, carries its own power, and relies on a built-in control system for self-control, allowing it to perform a range of underwater tasks flexibly and autonomously. They can autonomously conduct seabed mapping and data collection to determine the location and condition of oil and gas wells. AUVs can cover vast areas and provide high-precision information, offering valuable reference data for subsequent intervention operations.

Due to their lack of tether restrictions, AUVs have a wider range of lateral movement and can easily cross over wells in operations. Their autonomy is also higher, which can save on human resources (pilots) more effectively. However, the drawbacks are quite clear. Although they perform very well in tasks such as measurement and monitoring, they struggle with real-time precise manual control. Therefore, they are not suitable for many intervention cases, especially those with higher operational demands, such as leak plugging. Artificial intelligence technology can be easily integrated into these platforms, which will be introduced in the following sections.

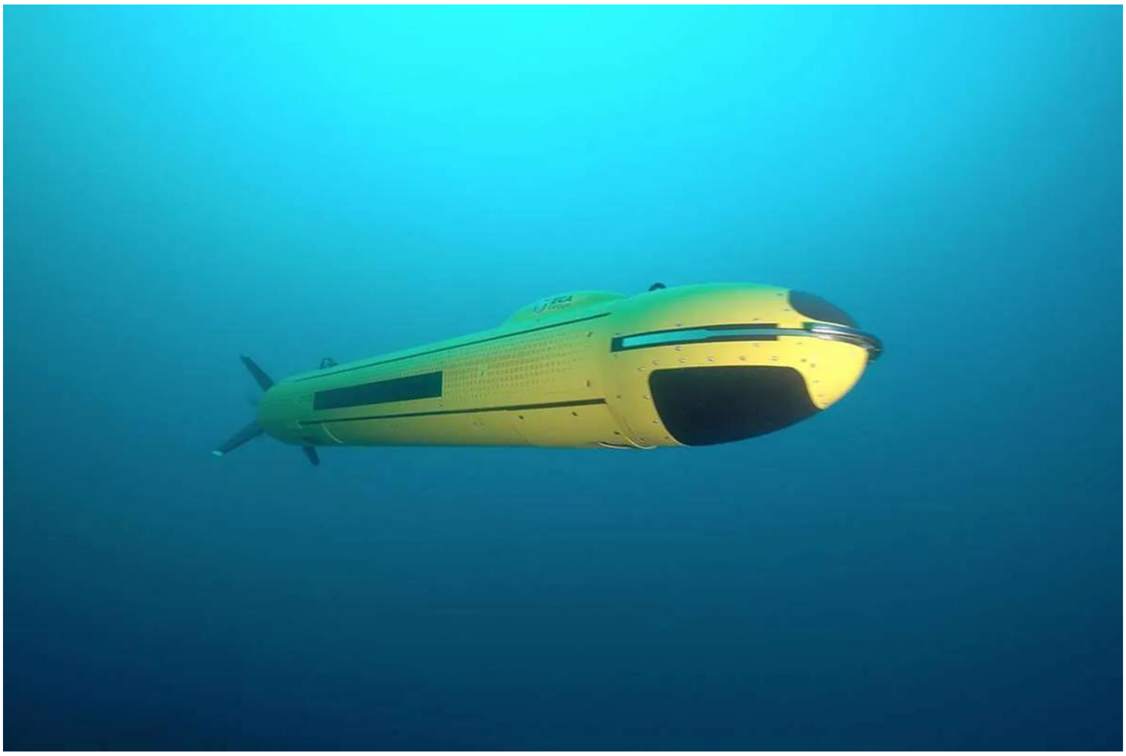

Fig. 8. A typical AUV without connecting cables to the mother vessel.

Fig. 9. A typical Human Occupied Vehicles (HOV).

Human Occupied Vehicles (HOV). An HOV is a type of manned small underwater vehicle, operating similarly to a mini submarine, shown in **Fig. 9**. HOVs are less commonly used in subsea well intervention due to their high cost and operational risks. However, in certain specific situations, HOVs carrying researchers and engineers can directly descend near oil and gas wells for onsite observation and manual operations. This direct human involvement can provide unique advantages in complex or emergency scenarios. Despite multiple safety precautions, whether personnel inside an HOV are truly safe remains a controversial topic.

Hybrid Vehicles. Some subsea vehicles share common traits of different kinds or possess different modes. The most typical example is some that can switch between ROVs and AUVs modes. **FIG. 10** shows an example. A subsea vehicle named ARV-i can switch modes through a mechanism similar to a wired base station. The base station is connected to the mother ship via an umbilical cord. This vehicle can work with the base station (in ROV mode) or operate independently (in AUV mode). This hybrid mode of operation offers a balance between endurance, manoeuvrability, and convenience. Indeed, underwater positioning is a challenge that is hard to completely overcome. Positioning based on a fixed base station makes it easier for the vehicle in AUV mode

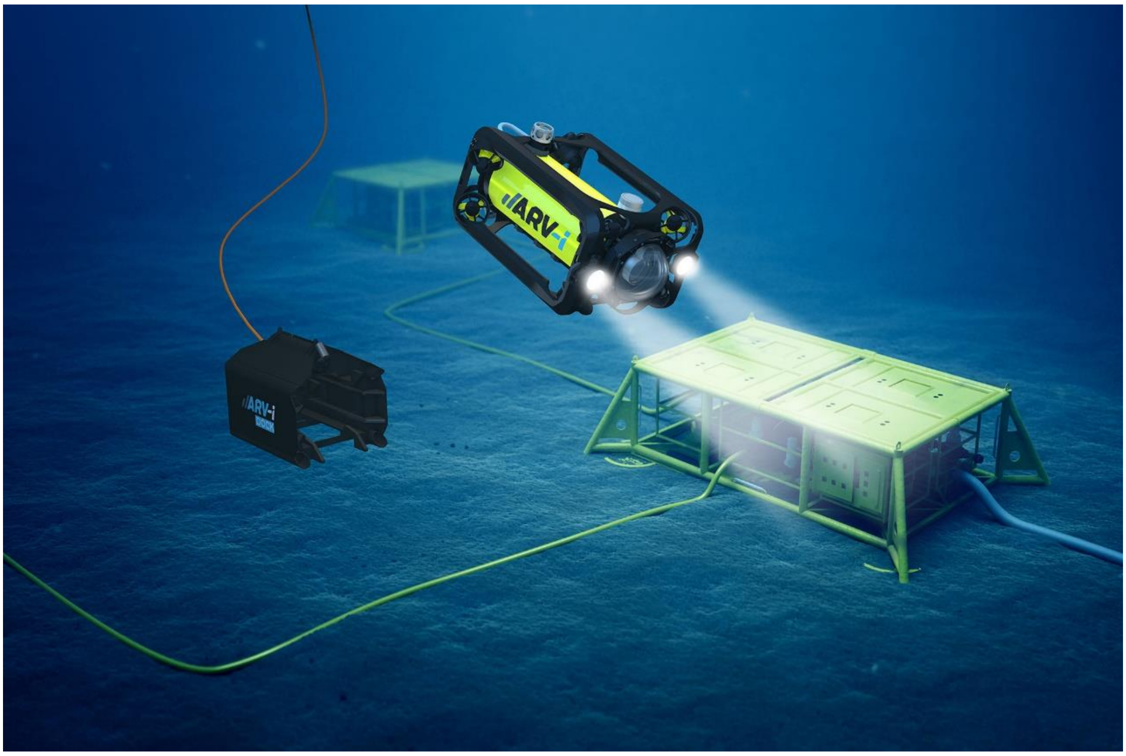

Fig. 10. Render of the ARV-i in operation underwater.

to complete tasks. Imagine a scenario: the crew wants to replace a known defective nut on a well tree and then conduct a scanning plan for the entire area to check for other potential risk points. Now, let's introduce this lovely versatile subsea vehicle. First, it enters the water as an ROV and gradually descends with the help of a LARS (Launch and Recovery System), approaching the equipment. Then, a professional pilot operates it to replace the nut. Afterward, it detaches from the base station and enters AUV mode, starting the automatic scanning. At this point, the pilot can certainly have a cup of coffee or eat a meal - at least I am hungry when writing this section of my CA paper. Since it does not consume its own battery during the descent and nut replacement phase, it still has sufficient battery life to complete the entire cruising process. If the scanning space is too large, it can even return to the base station for automatic recharging and complete the remaining workload.

Overall, in subsea well intervention operations, ROVs, AUVs, and sometime, HOVs each play distinct roles, collectively ensuring the safety and efficiency of oil and gas wells, completing different kinds of intervention workload. More new types of subsea vehicles are being developed, as described in later sections.

2.3 Intervention Equipment and Toolkits

In this section, intervention equipment and toolkits are briefly introduced. Intervention equipment refers to a series of specialized tools used for specific tasks, such as separating a section of piping from other parts. These tools often act on the piping and well structures themselves, rather than being carried by subsea vehicles. On the other hand, toolkits here refer to a combination of common tools that can be used in the intervention process. They can sometimes be mounted on small mobile carriers like ROVs for maintenance operations. Frontiers for these equipment are also introduced here, instead of discussing in Section 4., in order for better reading.

Coiled Tubing. Coiled tubing is a continuous length of flexible pipe used in subsea well interventions. Its flexibility allows it to be inserted directly into the wellbore through the wellhead, facilitating the delivery of tools, fluids, or cleaning operations. Coiled tubing eliminates the need for traditional rig-based pipe handling, significantly increasing the efficiency and safety of intervention operations. It can also be combined with other tools, such as perforating guns or washing tools, for more complex intervention tasks. **Fig. 11** shows a typical coiled tubing system. Huang et al., studied the flow behavior in a coiled tubing system [16]. Mohammed et al. reviewed the coiled tubing systems as a well stimulation technology [17]. Zhang et al. used machine learning method to predict the parameters for a coiled tubing system [18].

Fig. 11. Coiled tubing system by Tucker Energy Services Co., Ltd.

Packers. Packers are sealing devices used in wells to isolate specific sections. For intervention process, service packers are often used, with the purpose of optimize production, injection, or cleanup treatments with mechanically set, retrievable packers [19]. In subsea well intervention operations, packers play a crucial role in controlling well pressure and preventing oil and gas leaks. They are used to separate different production zones or water layers within the well. The design and selection of packers are tailored to the specific conditions of the well and the requirements of the intervention operation, ensuring reliability and safety. **Fig. 12** shows a kind of wireline-set retrievable bridge plug, especially designed for service packers.

Fig. 12. A kind of wireline-set retrievable bridge plug for subsea service packers, developed by SLB Group.

Blowout Preventer (BOP). A blowout preventer is a critical safety device designed to control well pressure and prevent blowouts [20], shown in **Fig 13**. In subsea well intervention operations, the BOP is typically installed at the wellhead and can quickly shut off the flow of oil and gas from the well. It consists of multiple valves and sealing systems that provide effective pressure control under various conditions. Additionally, the BOP can be used in conjunction with other pressure control equipment to enhance safety measures during interventions. BOP can be used in a wide range of subsea operations where well killing (P&A) is an important part among them. Referring to the patent, a BOP system was designed especially for intervention work [21]. In addition, the failure problem of BOP has been studied by many researchers, and various solutions have been proposed [22-24].

Subsea Toolkit. This kind of subsea tools are often integrated in ROVs, providing different engineering abilities for them. Typical tools include manipulator arms, cutting tools, cleaning tools, injection tools, measurement and inspection tools, sealing and clamping tools, hot stab connectors, torque tools. They play a key role in the subsea well intervention process of ROVs (or other Subsea vehicles).

Fig. 13. A typical Blowout Preventor (BOP) system.

3. Intervention Process

As introduced in the above sections, the subsea well intervention is aimed at maintaining, optimizing, and enhancing the performance of subsea wells, as well as plug and abandonment operations. In this section, the typical processes will be introduced. Regardless of the purpose of a subsea intervention, they usually include the following steps to ensure the safety and efficiency.

Detection and Measurement. Understanding the current status of a subsea well is very important. For a well that has experienced an emergency, the point of the incident and the cause of the accident need to be investigated immediately. For wells that require modification or are about to be decommissioned, their operational status is also worthy of attention. On the one hand, internal detection tools are used. This includes readings from various sensors on the well (especially the Christmas tree) and the characteristics of the produced oil and gas if it is still in production. On the other hand, external detection methods are more important. Subsea vehicles equipped with various sensing devices will conduct comprehensive inspections (especially for fault screening). Compared to internal sensors, these external detection methods often yield more

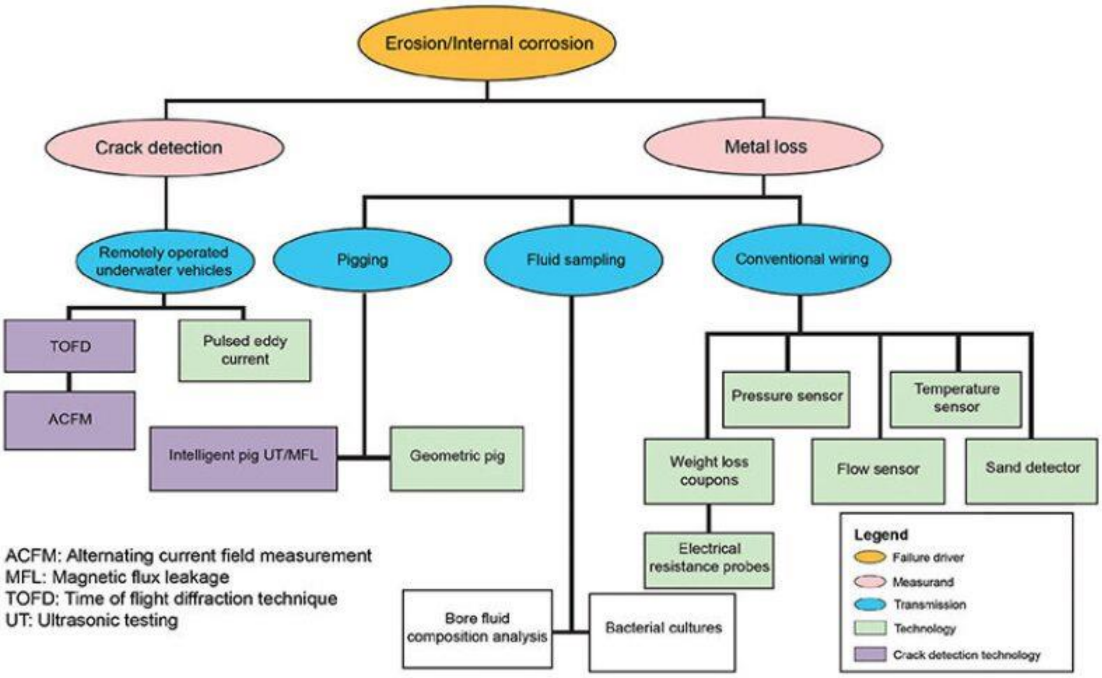

Fig. 14. A baseline map compiled by the SURF IM joint industry project.

satisfactory results due to their better control over the objects of detection. The final inspection report will reflect the fault conditions or operational status of the subsea well. **Fig. 14** prevented a guiding map regarding the technologies available to assess and treat specific defects caused by erosion and internal corrosion.

Intervention Planning. Based on the results of the tests described above, in conjunction with the goals of the intervention, a plan for the intervention will be developed in its entirety. Typically, this includes a list of equipment (and tools for equipment that can be replaced), the expected mode of work, the person who will perform it, the time of execution, etc. Another area that needs special mention is safety, both of personnel and equipment. A series of safety precautions and emergency handling programs are also developed together to ensure a quick and correct response when danger arrives.

Preparation and Execution. All equipment for the intervention will be transported to the target by means of mobile platforms or other means of transportation. Then the necessary isolation lines will be constructed and the subsea vehicles will be released and submerged. They will carry out specific elements of the intervention in accordance with the plan.

4. Recent Advances

The academic community and industrial companies have always been innovating in the field of subsea intervention, proposing many new technologies and equipment. They are briefly reviewed and introduced in this section.

Emergency Equipment. On the one hand, traditionally subsea engineering equipment is modified or redesigned for intervention purpose, and generally, they are often focusing on a kind of fixed tasks, such as fastening and cleaning. For example, as a part of Source Control Emergency Response Planning (SCERP) of WILDWELL, the Well CONTAINED Subsea Capping Solutions (**Fig. 15**) are designed for subsea uncontrolled wells. Among them, its main tasks include capping stack installation plans and other subsea fastening tasks. Certainly, it is also capable of executing additional specified subsea operations, such as drilling, surveying, and monitoring. A complete system includes four parts: subsea capping stack, subsea dispersant package, debris removal package, and power supplier.

Fig. 15. Well Contained Subsea Capping Solutions for emergency

Subsea Robotic Agency. On the other hand, with the continuous development of technologies such as computer vision and multimodal sensing, artificial intelligence (especially unmanned systems) has gradually begun to play a significant role in subsea engineering. Soft robots and biomimetic robots are widely applied underwater. Although they are currently mostly in the development or experimental stage, their potential is considerable, and their application range is broad. For subsea intervention, these new technologies can further shorten response times or reduce the cost of intervention.

Shown in **Fig. 16**, Eelume is a kind of new robotic device, defined as inspection, maintenance and repair (IMR) robot, and designed for deep water cases. This project is by a start-up (with the same name of the robot itself) spun off from the Norwegian University of Science and Technology, providing robotics solutions. It has a snake-like appearance, and integrated with sensors, controlling modules, and a specifically designed payload interface. This payload interface can be used to install tools for operating underwater valves and a cleaning brush for removing marine organisms and sediments. The robot has an overall length of approximately 6 meters and can remain at a depth of 500 meters for 6 months, with a single mission endurance of about 20 km. This new type of robot is an exploration in subsea engineering that represents a combination of industrial and academic research. In the past, efforts to focus on the pass-through nature of robots have often been seen on university campuses rather than as a tool that can be purchased.

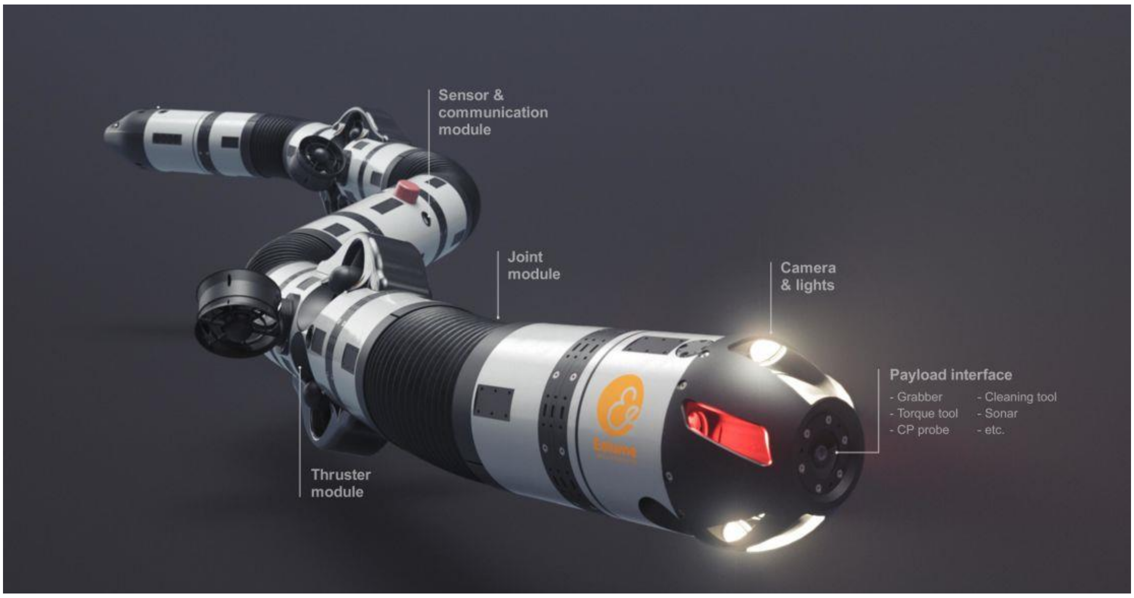

Fig. 16. Eelume "snake-like" subsea IMR robot.

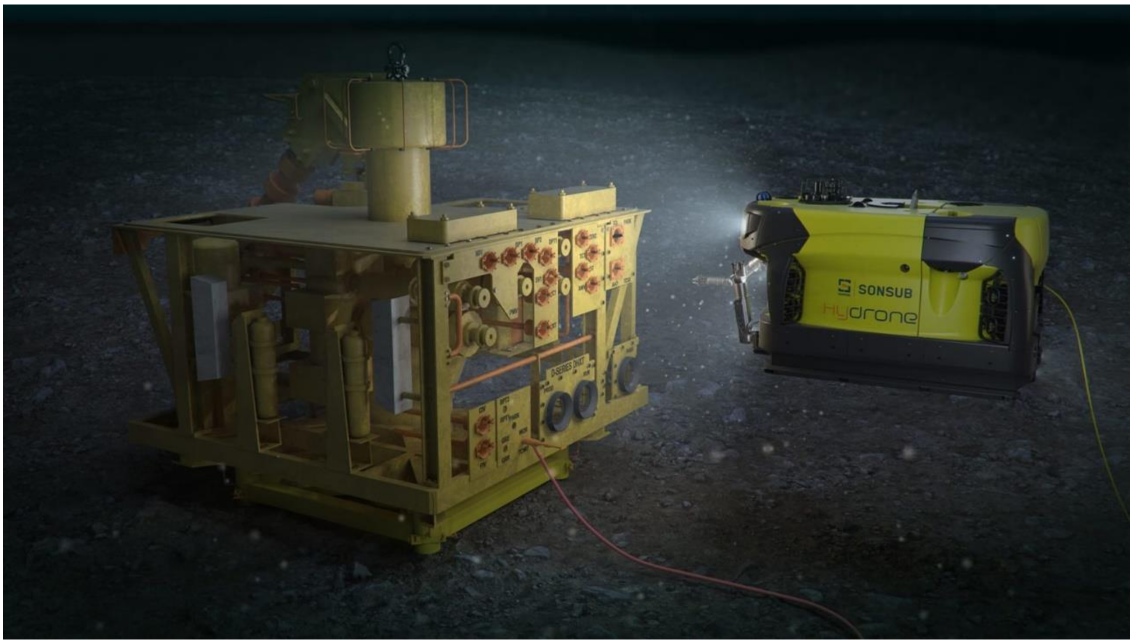

Fig. 17. SAIPAM Hydrone-R system for intervention purposes.

SAIPAM designed Hydrone-R (**Fig. 17**), which means Hybrid ROV/AUV System for subsea engineering. Developed since 2019, it has been the first Underwater Intervention

Drone (UID) in operations since June 2023. The maximum working depth comes to 3000m, and resident also for 6 months, same as Eelume. Due to the official documents, the tools for different application scenarios could be torque tool, contactless cathodic protection measurement, acoustic survey, environmental survey and monitoring, and water jet. Among them, emergency intervention is their main focus. Additionally, it has three modes: ROV mode (300 m controlling), Wireless ROV mode (50 m), and AUV mode (more than 20 km).

In this field, many universities and research institutes have also showcased their work. Palomeras et al. proposed an I-AUV docking method, which could be used for intervention on a Subsea Panel [25]. Focusing on the maintenance of permanent underwater structures as well as the recovery of benthic stations or black-boxes, this light-weight intervention AUV (I-AUV) can automatically dock with underwater equipment and complete designated maintenance tasks. During the docking identification process, they also used computer vision technology to assist in docking. Mohammed et al. used deep learning techniques to complete pose estimation during the subsea intervention process [26]. Their main goal is to detect and predict the 6-DoF pose for relevant objects (fish-tail, gauges, and valves) on a subsea panel under varying water turbidity. Typically, the seabed is turbid, filled with various unpredictable dirt and obstacles, hindering the application of visual sensing technology. However, this system, designed with high robustness, is able to achieve an average precision of 91%. Transeth et al.'s work combines the advantages of the aforementioned approaches [27]. They introduced their new methods for autonomous inspection, maintenance, and repair (IMR) in subsea oil and gas operations with Unmanned Underwater Vehicles (UUVs). These techniques have been successfully tested. They also classified existing missions and equipment into three levels: mission-level, task-level, and vehicle-level. Technologies including pose estimation, autonomous navigation, target recognition, and automatic maintenance have been packaged into a framework, providing significant industrial guidance value. Efosa et al. maps the factors affecting job schedule efficiency in subsea inspection, maintenance, and repair (IMR) services, based on literature reviews and expert interviews [28]. Influencing factors include weather disruption, water depth, job complexity, job uncertainty, and IMR equipment availability. The findings highlight the importance of these factors in planning and executing IMR services for offshore oil and gas installations. Developed by Vassilis et al., the autonomous subsea intervention robot uses Doppler velocity log (DVL), pressure, and attitude and heading reference system (AHRS) sensors for navigation and is equipped with a laser scanner providing non-coloured 3D point clouds of the inspected structure in real time [29]. The object recognition module recognises the pipes and objects within the scan and passes them to the SLAM, which adds them to the map if not yet observed. Otherwise, it uses them to correct the map and the robot navigation if they were already mapped.

5. Industrial Key Players

The key players (companies) in the subsea well intervention area include Halliburton Company, Schlumberger Limited, Baker Hughes Company, China Oilfield Services Limited, etc. In this section, two top companies (Halliburton and Baker Hughes), together with their honourable intervention solutions, are introduced one after another.

One point of special note is that, except for the citation contents, all the content comes from the official website of the corresponding company to ensure the accuracy of the information [30, 31].

5.1. Halliburton Company

Halliburton Company is an American multinational corporation and the world's second largest oil service company which is responsible for most of the world's largest fracking operations [32].

For detection and assessment, Halliburton developed Electromagnetic Pipe Xaminer V Tool. This tool could accurately pinpoint the casing defects and metal corrosion in up to five tubular strings throughout the well. Shown in **Fig. 18**, Acoustic Conformance Xaminer (ACX) is another analysis tool, using acoustic methods (hydrophone array) to identify the leaks and flow around the wellbore and behind pipe in real time. They also designed InSite for Well Intervention (IWI), which is a web-based design software to create solutions for well intervention challenges.

More technologies from Halliburtion are especially designed for P&A process. Spectrum IRIS is a real-time high-resolution down-view camera to gather maximum downhole insight for best planning and validation of abandonment operations. They also have a service namely Well Assure, in order to safely plug the wells and help prevent carbon emissions.

Interestingly, they built a “Halliburton Labs”, from which start-ups in energy industry can obtain technical support for innovative product design.

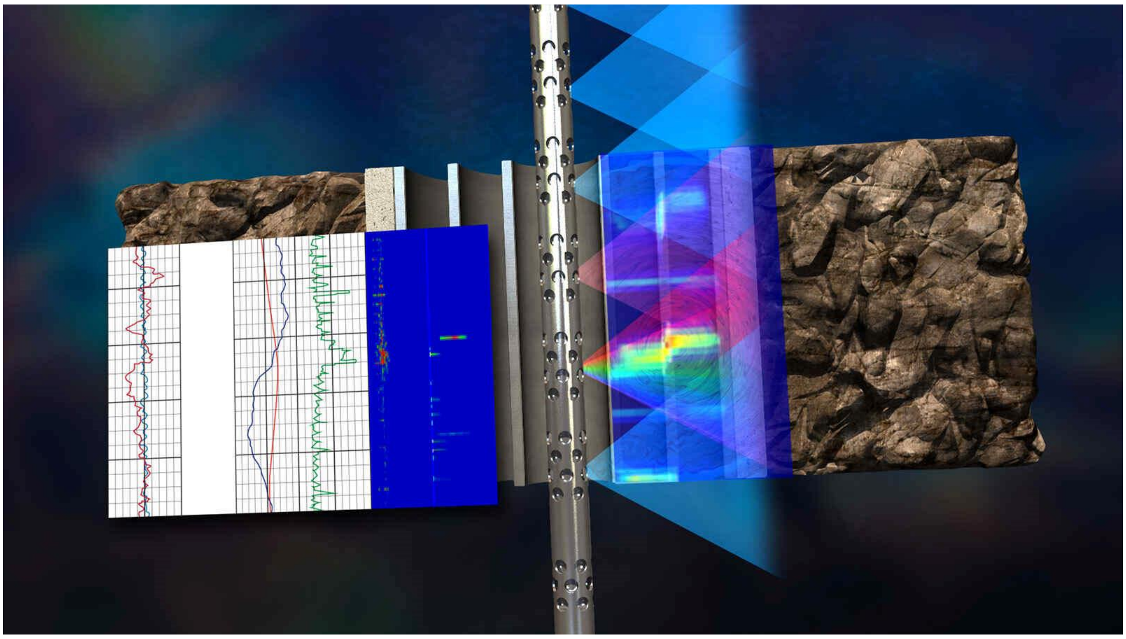

Fig. 18. Halliburtion Acoustic Conformance Xaminer.

5.2. Baker Hughes Company

Baker Hyghes’ intervention solutions are including four products: Prime, AquaCUT, Telecoil, and Certia. They have different sub-techniques (e.g., different tools) and application scenarios.

Prime refers to the solutions for complex mechanical intervention, namely rotational services (debris or component milling) and high expansion completion component manipulation. It brings advanced e-line intervention solutions to limited rig-up height operations. AquaCUT Plus relative permeability modifier (RPM) from Baker Hughes, is a subsurface water conformance product that decreases the water cut in mature sandstone and carbonate wells, reducing associated processing and disposal costs while also extending the productive life of the well. By selectively targeting only the water phase of produced fluids, AquaCUT Plus RPM products reduce the amount of produced water with minimal impact on hydrocarbon production. TeleCoil intelligent monitoring and telemetry service provides critical downhole logging data through distributed acoustic and temperature monitoring, for more targeted interventions and stimulations in a single run. Certia is a free pipe depth detection method (**Fig. 19**). When a pipe becomes stuck, it can be used to determine the location of the blockage and thus assist in troubleshooting the problem. With the help of their self-produced cutters and other intervention tools, the pipelines could be recovered in 24 hours with their service.

Fig. 19. Baker Highes Certia technology for free pipe depth detection.

6. Conclusion

In this CA paper, subsea well intervention technology is reviewed from different perspectives. Firstly, the background is introduced, supporting the need of subsea well intervention techniques. Due to the high pressure, high salinity, and various threats present in the environments where wells are located, they usually require relatively frequent maintenance, which is also quite challenging. Additionally, when a well reaches its life limit, plug and abandonment operations are needed. In some cases, wells need to be modified to adapt to different production objectives or to increase their output. Then, the main equipment for subsea well intervention is introduced. One type is platforms, including rig-based systems and vessel-based systems. The former has higher individual performance and can complete more complex heavy-duty tasks, while the latter is more flexible and manoeuvrable. Currently, rig-based systems are often used for different wells in a single oil field, whereas vessel-based systems can work across oil fields. With the development of equipment miniaturization, vessel-based systems could become a trend. Another possible direction is the replacement of risers with riserless systems, for similar reasons. Then, underwater robots (represented by ROVs) are introduced and categorized. As the focus shifts to recent years, some companies and university research groups have developed many new devices, constantly pushing performance limits and expanding application scenarios. Two main areas of focus are including: the development of new large-scale equipment dedicated to intervention (rather than sharing equipment platforms with construction and operations). The second is the introduction of artificial intelligence. New technologies such as computer vision, deep learning for 3D reconstruction, and soft robotics are being applied, tested, and even commercialized in this field. Some of these are briefly introduced in this text. More AI-driven subsea well intervention techniques are on the way and will become mainstream in the future. Finally, the key companies of subsea intervention industry are listed, from which two of them are selected for a more detailed introduction, including Halliburton and Baker Hughes.

In one word, subsea well intervention is the combination of all the techniques and solutions regarding “sustainability development” for subsea well, leading the industry to a brighter future.

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