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## Abstract

The onset of electrification and increasing penetration of renewable energy resources as well as prioritization for greater environmental, social and governance factors in the offshore energy sector will lead to the emergence of disruptive technologies. The offshore inspection, repair and maintenance (IRM) market was USD 8.93 billion in 2020 and is projected to grow to USD 18.04 billion by 2028 [1]. At present, remotely operated vehicles (ROVs) generally supported with large offshore support vessels (OSVs), have established themselves as indispensable for offshore IRM operations. Key emerging technologies such as 3D computer vision, mixed reality, digital twinning, and machine learning, coupled with significant advances in robotics, automation, sensors, and communication now make it possible to consider performing a range of undersea tasks using undersea vehicles without a tether, but under careful human supervision. It is now possible to radically redefine the meaning of the words "tethered system" through a hybrid approach by including virtual tethering via high frequency acoustic or optical communication at a short range, and with an extremely small optical fiber base station providing remote surface connectivity. By collaborating with an onshore/offshore remote human operator and a digital twin of the environment, battery-powered, tetherless hybrid underwater vehicles (HUVs) will be able to perform a range of tasks at a remote location that might otherwise require a conventional ROV and a support ship on site. The Collaborative Human Robot Inspection & Intervention System (CHRIIS) is aimed towards providing remote intelligent tetherless solutions to inspection and light intervention of offshore marine assets.


## Introduction

Our oceans cover more than two thirds of the earth's surface and support an estimated 90% of the life forms on our planet. They constitute one of the main resources for food, employment, and economic revenue, with rich chemical and biological activities, mineral deposits, as well as alternative and sustainable energies. From a scientific point of view, the deep ocean is thought to hold the secret to the origin of life. At the same time, the oceans also harbor a vast cultural heritage in the forms of archaeological sites yet to be explored. Given the complex and harsh nature of the marine environment and the inability of humans to submerge to deeper depths or staying underwater for long periods of time necessitates the need for unmanned marine robotic systems.

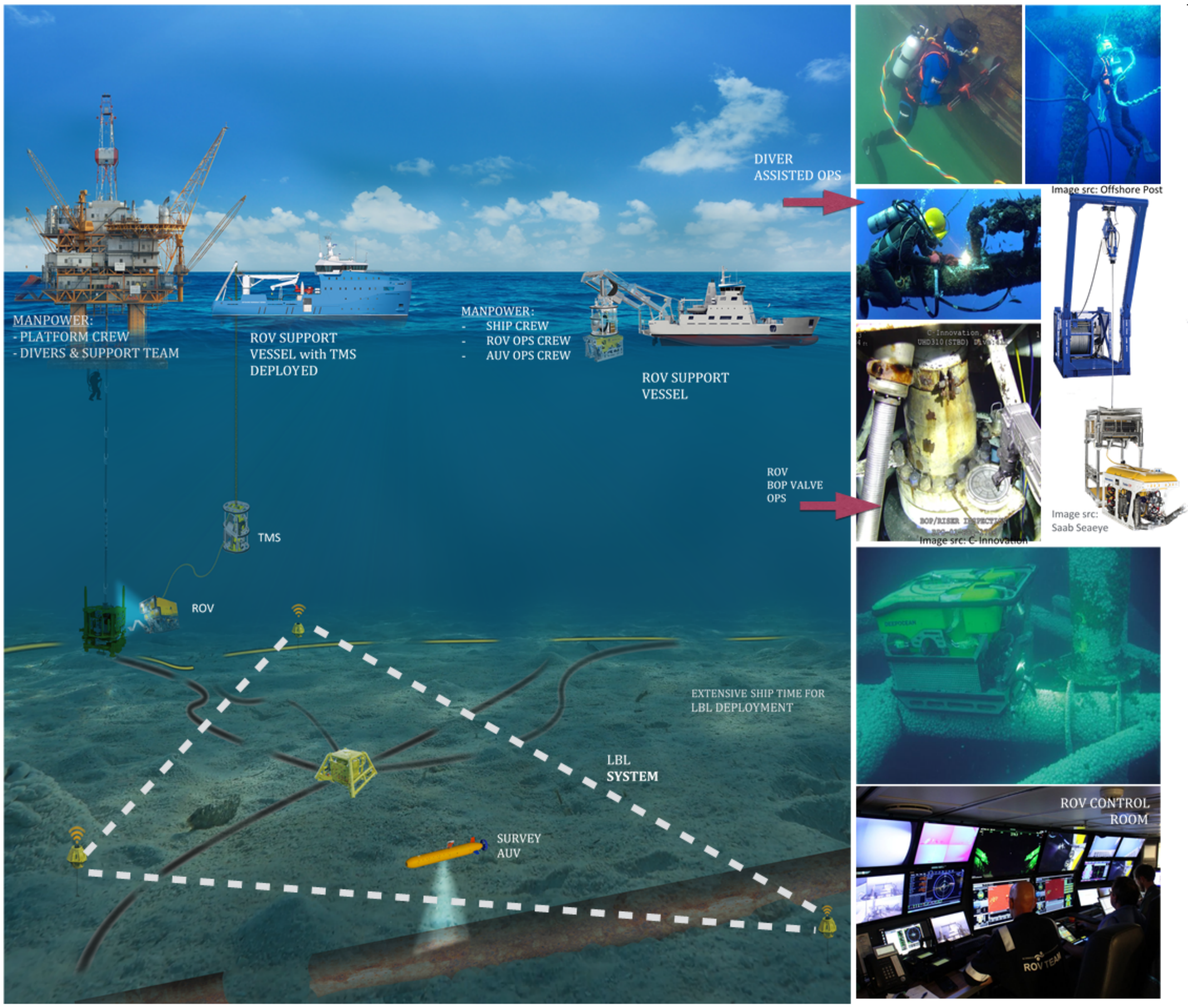



**Figure 1: Current State of Underwater Operations**

The term *marine robotics* is used very generally to describe unmanned systems operating in marine environments, both surface and subsea. In the subsea domain, unmanned systems fall into two major classes: remotely operated and autonomous. Figure 1 illustrates the current state of subsea operations.

Remotely operated vehicles (ROVs) have established themselves as an indispensable technology for offshore operations, primarily for asset integrity management (e.g., Saab Panther, Phantom S2, Videoray Pro, Super Scorpio, Nereus, Schilling Robotics UHD). An operator on a support ship controls and navigates the ROV via an umbilical cable (also known as a *tether*). The tether generally provides power and the necessary communication links between the ROV and its operator. However, the tether is also the key drawback of this technology as it necessitates a tether management system (TMS) and a large offshore support vessel (OSVs), limits operations in high sea states, increases operational risk due to potential for entanglement, and prevents the use of multiple ROVs in the same operational area.

ROV operations demand high operational expenditure (opex) as the day rate for OSV for work-class ROVs is in the range of hundreds of thousands of dollars, depending on the size, nature and area of operation, and the need for highly skilled operators. Moreover, the operations involving ROVs are complex as they involve management of the long and heavy tether that is attached to the vehicle. Furthermore, there is always a need for an open weather window due to their reliance on surface support. At present, most industrial ROV operations are manually controlled, with little or no automatic control functions or autonomy. Thus, operational efficiency is highly dependent on the experience of the human operator. Autonomy in ROV operations is a stepping stone towards increasing the efficiency and thereby reducing the operating expenditure and improving the overall health, safety and environment (HSE) standards [2], [3].

The Autonomous underwater vehicles (AUVs) on the other end of spectrum, relying on onboard power supply and intelligent control and navigation units, have become a recognized tool for seafloor mapping, surveys and mine counter measure operations (e.g. Remus, Hugin, LAUV, Starfish, Bluefin, Autosub) [4]. While autonomy with AUVs is good for the above-mentioned operations, more complex offshore IRM require real-time command and control with "human in the loop". However, without a tether, the communication between an AUV and its human operator is very limited. Since radio waves do not propagate well in water, acoustics is the primary means of communication. But acoustic communication is slow, has high latency, and is known to be notoriously unreliable. Without real-time feedback to the human operator, usage of AUVs has been mostly restricted to mapping and survey operations, and almost non-existent in IRM operations. The risks involved is large enough for an ROV operator to be unwilling to trust an AUV to make critical decisions autonomously, requiring the need for supervised autonomy [5].

More recently, a new class of vehicles called the hybrid underwater vehicles (HUVs) are emerging that combines the best features of a ROV which is connected to a ship in order to transmit data and video feeds and an AUV that can swim freely covering larger areas. The Sabertooth [6], Nereus [7] and more recently Aquanaut [8] are such underwater vehicles that are closing the gap between conventional ROVs & AUVs. The Collaborative Human Robot Inspection & Intervention System (CHRIIS) is a supervised autonomy framework that is aimed towards bridging this gap by providing remote intelligent tetherless solutions for IRM operations.

## Collaborative Human Robot Inspection and Intervention System

Key emerging technologies such as 3D computer vision, mixed reality, digital twinning and machine learning, coupled with significant advances in robotics, automation, sensors, and communication now make it possible to consider performing a range of undersea tasks using undersea vehicles without a tether, but under careful human supervision. It is now possible to radically redefine the meaning of the words "tethered system" through a hybrid approach by including ***virtual tethering*** via high frequency acoustic or optical communication at a short range, and with an extremely small optical fiber base station providing remote surface connectivity. By collaborating with an onshore/offshore remote human operator and a digital twin of the environment, battery-powered, tetherless HUVs will be able to perform a range of tasks at a remote location that might otherwise require a conventional ROV and an OSV on site. To enable this supervised autonomy framework for IRM, following key components are being developed as part of CHRIIS:

- Vehicular technology focusing on system agnostic command & control framework,
- High-speed wireless underwater communication,
- Data compression & video streaming, and,
- Latency management via digital twinning of the operating environment.

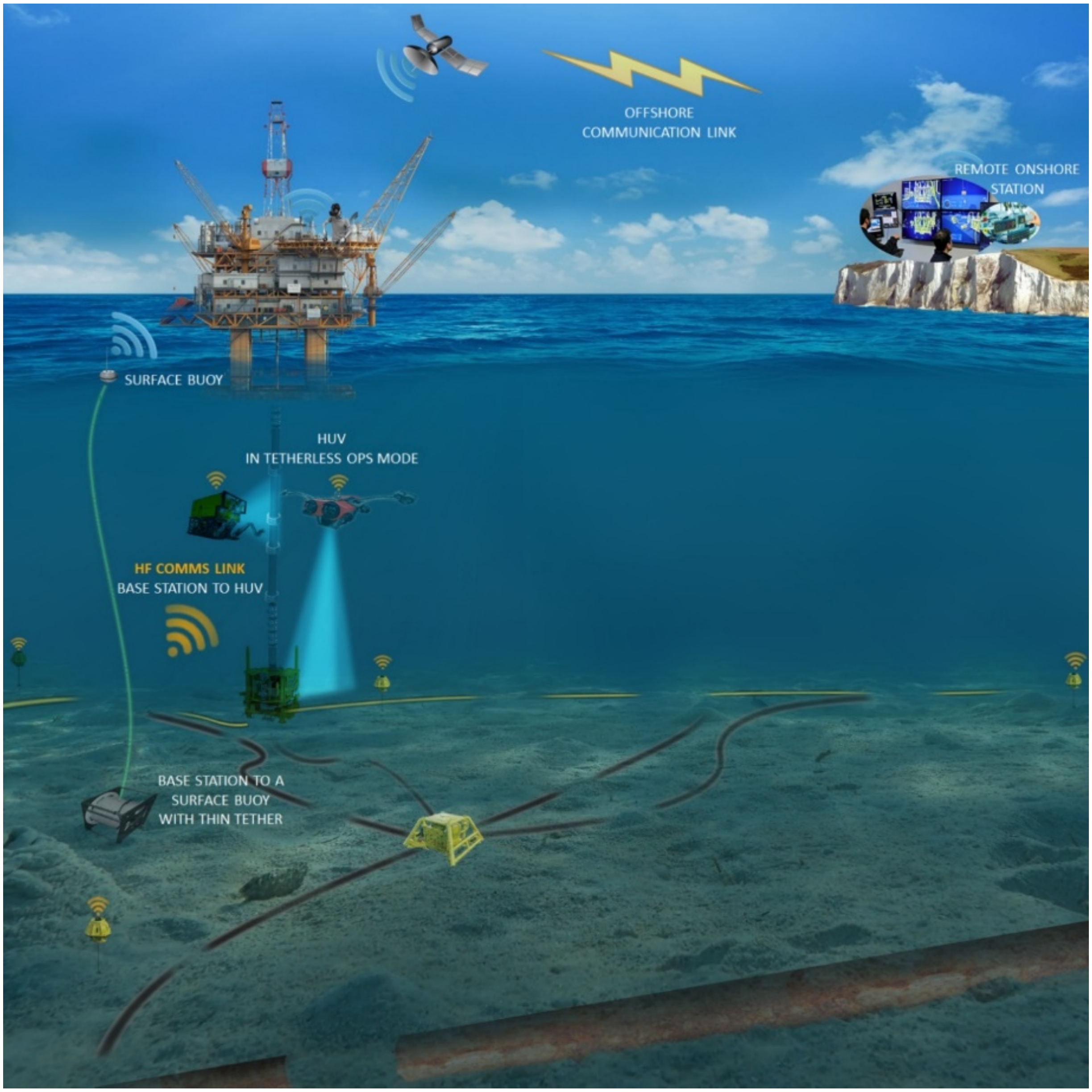



**Figure 2: Concept of Operations**

The development of these component technologies offers the potential to transform ROV type operations. Operations may be performed at much lower operating expenditure as the dependence on OSVs are greatly reduced because of the removal of specialized TMS and vehicle handling equipment, and a reduced need for dynamic positioning capability. Moreover, the operational weather window can be significantly extended as the tetherless underwater robot is decoupled from surface disturbances.

## CHRIIS – Concept of Operations

In this section, we outline the concept of operations using inspection and light intervention of an offshore structure, as an example application.

**Step 1** - An inspection class autonomous vehicle equipped with exteroceptive sensors and navigation payload is deployed in the vicinity of the structure to be inspected.

**Step 2** - The inspection class vehicle autonomously maps the structure that is being inspected, using state-of-art photogrammetry, sensor-fusion, mapping, and localization technologies. Photorealistic multi-sensor 3D models of the structure are then reconstructed offline. Combined with our hydrodynamic understanding of the environment, this creates a digital twin of the operating environment. A sample of models that can be built is illustrated in Figure 3.

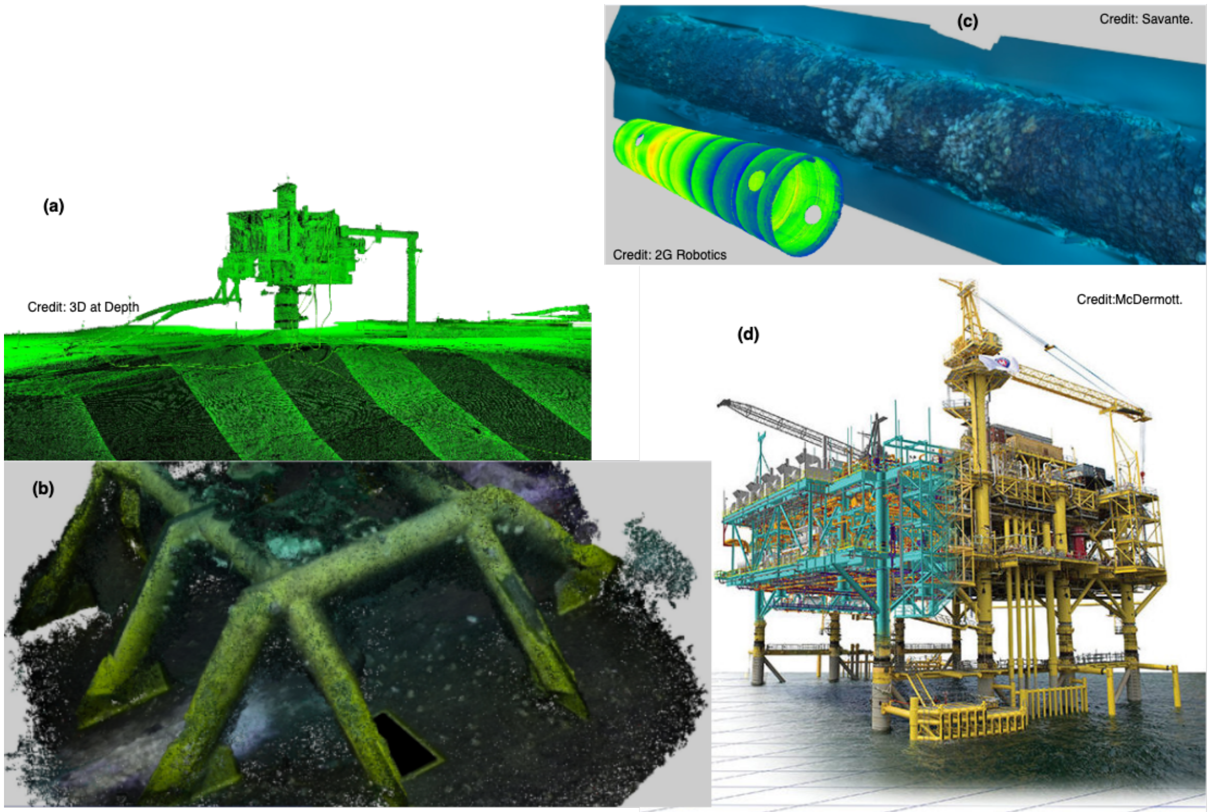



**Figure 3: A sample of 3D models & digital twin**

**Step 3** - A human inspects the 3D model to determine if a closer look or intervention is required. Assisted by automated data analysis & machine learning technologies, the human inspector will be able to quickly and reliably determine if:

- **A.** an anomaly is detected during inspection and needs a closer look with a different sensor,
- **B.** A closer look into certain parts of the structure is needed, or
- **C.** certain light interventions need to be performed on the structure.

**Step 4** - If a closer look or light intervention is required, an HUV is deployed. It autonomously navigates to the area of interest, and then switches to a remote-operated mode, allowing a human operator to control or supervise further operations. The HUV allows human-in-the-loop remote operations like an ROV, while being tetherless like an AUV, and therefore being able to swim freely to cover a larger area without risk of entanglement. To further reduce the need for continued surface support, an ad-hoc underwater base station may be deployed along with the HUV. Once deployed, the base station (illustrated in Figure 4) establishes a high-speed short-range underwater communication link with the HUV, and a tethered link to a surface buoy, which in-turn establishes a communication link to a remote onshore ground station. To provide high quality imagery and reduce the latency, the digital twin developed in Step 2 is used to drive a mixed reality environment for the onshore operator. This mode of operation is dubbed as ***HUV in tetherless remote operations mode***. To enable this mode key component technologies such as latency and bandwidth management, high-speed underwater wireless communication, and content aware data compression are being developed.

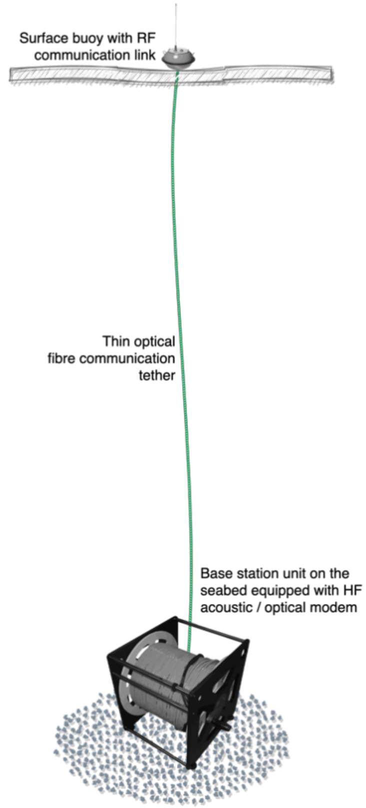



**Figure 4: A base station setup**

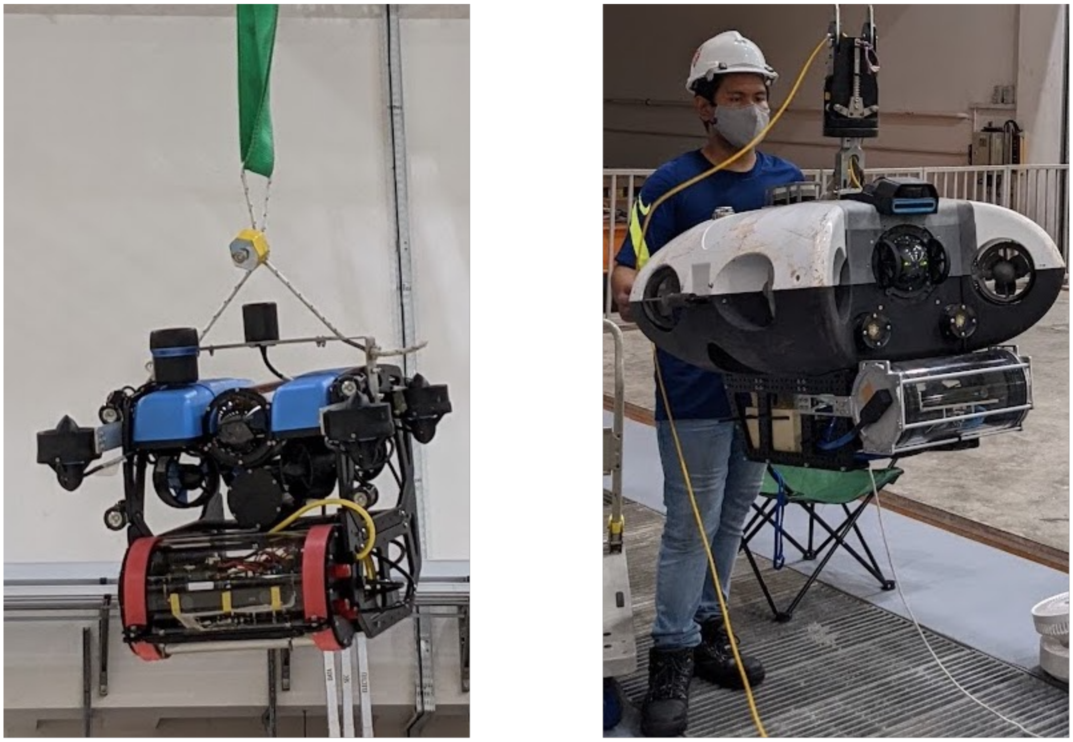
**Step 5** - The HUV is equipped with manipulators and end effectors for ultra-light intervention operations. The HUV carries out necessary operations in a collaborative manner under the supervision or control of the human operator.

## Development of Component Technologies

ROVs use the tether to provide high-speed low-latency communication. The key concept of operations in CHRIIS is to operate HUVs without a tether, while still providing remote control and supervision. Underwater wireless communication available today is unable to provide the speeds, robustness and latency required for remote control of ROVs. This challenging task, however, can be solved through some key innovations that we outline below.

## Vehicular Technology

The supervised autonomy framework of CHRIIS is being designed to be vehicle agnostic. Most AUVs control design have been centered around single thruster torpedo vehicles due to their widespread commercial adoption. However, the HUVs built for testing component technologies in CHRIIS (Hydra & Ikanbilis) have the hovering capability near structures with the ability to control individual thrusters in coordination to achieve the desired motion in full 6 independent degrees of freedom.



(a) (b)

**Figure 5: (a) In-house built HUV- Hydra (b) Ikanbilis from BeeX Autonomous Systems**

## High-speed Wireless Underwater Communication

Since electromagnetic waves do not propagate well in water, acoustics is typically used for mid-to-long range underwater communication [9]. Acoustic communication systems have a reputation to lack robustness, even at low data rates. Our team at TMSI has developed robust mid-range communication systems over the past 15 years, and these systems are now commercially available through Subnero Pte. Ltd., a spin-off company from NUS that specialized in underwater communication. Subnero has previously demonstrated a high-speed acoustic modem that provides sufficient data rate for short-range (up to about 100 m) low-quality video. Similar efforts have yielded some success in other parts of the world to [10], [11], but the technology is still immature and insufficient for our needs. Optical modems have also been shown to work well in clear waters at short ranges (typically 20-50m) [12], but their performance rapidly degenerates in turbid waters. As part of CHRIIS, we are developing technology for robust high-speed acoustic communication along with our industry collaborator. We are leveraging on embedded GPU technology to facilitate use of computationally complex algorithms for equalization, diversity combining, and forward error correction (FEC), to help us improve communication performance. Based on previous work on communication in impulsive noise [13], we are developing new receiver algorithms. These algorithms will help improve communication in snapping shrimp noise, which is common in places like Singapore, Gulf of Mexico, and Brazil, where such systems are likely to find operational use. We expect that these improvements will enable us to achieve data rates of up to 100 kbps over about 100 m robustly. This combined, with data compression (described in the next sub-section), will be sufficient for CHRIIS to stream real-time video.

While Singapore waters exhibit high turbidity, many other target operating environments have clearer waters. Optical modems might provide a good option in such environments [12]. Rather than have to choose between acoustic and optical, we have integrated both systems into a common software framework[14] that transparently manages data flow over both mediums. In favorable conditions, this may allow much higher data rates by leveraging both acoustic and optical channels simultaneously. In poorer conditions, diversity combining across the two channels will allow a level of robustness that would not be possible with either modality independently. This has resulted in the development of an opto-acoustic underwater communication system that will outperform any acoustic or optical modem in similar conditions. We expect that such systems might even provide some performance advantage in turbid waters, with the additional noisy data from the optical system providing sufficient information for error correction on the acoustic system. The testing of opto-acoustic underwater communication system is expected to be completed by the third quarter of 2023.

## Data Compression & Video Streaming

While a robust 100 kbps link is better than the state-of-art commercial offering today, it alone is only sufficient for a low-rate video streaming using available video compression technology. We need another innovation to reduce data rate for video streaming in order to be able to meet CHRIIS video streaming requirements.

Recall from the concept of operations that we develop a digital twin of the operational environment using the data collected in Step 2. This digital twin uses images captured during the autonomous inspection stage to build a photorealistic 3D model. This can be used to render a virtual “camera” image onshore by simply knowing the location and pose of the underwater vehicle. The underwater vehicle can also render the same image, and only transmit differences between the real camera image and the virtual “camera” image over the high-speed wireless link. Such differences are typically small and have low entropy, and therefore can be heavily compressed for transmission. This will allow us to be able to transmit high-quality video with the modest data rates that will be available over the high-speed wireless communication system described in the previous section.

## Latency management via digital twinning

Wireless underwater video streaming, as described in the previous two sub-sections, will allow an operator to see what is happening underwater. When the operator commands the vehicle to act, he expects to see an immediate corresponding update in the video stream. Research has shown that a latency of more than 50 ms is noticeable, and the operator performance degrades rapidly with increasing latency [15]. Hence it is important to keep the latency small.

Latency and throughput are often trade-offs [16]. In order to achieve high data rate for video streaming, it is inevitable that latency will suffer. Additionally, the slow speed of sound in water, and the potential use of long-range RF / satellite communications for onshore remote operations, adds significant latency to the system. Latencies of several hundreds of milliseconds are inevitable, but unacceptable. We resolve this problem with the use of the digital twin that we built in Step 2 of our concept of operations. The digital twin not only had a photorealistic 3D model, but also has a hydrodynamic vehicular response model as part of it. When an operator commands the vehicle, the command is not only sent to the vehicle, but also to the onshore digital twin. The digital twin reacts immediately, with almost no latency. It provides video feedback to the operator immediately, and hence the operator does not experience the long latency that is inherent in the communication channel to the actual vehicle. In most cases, the digital twin will be able to accurately predict what the vehicle will do and what it will see, and hence this immediate feedback is accurate. However, small errors are continuously corrected using the slightly delayed data stream back from the vehicle, and not allowed to accumulate. In the rare cases that the predictions have a large error due to unforeseen disturbances in the real environment, the video stream is updated within a few hundred milliseconds to reflect reality. As long as these occurrences are not very frequent, the operator experience and performance are not significantly affected. We have already undertaken a feasibility study of this idea through an underwater simulator by introducing latencies and have found it to hold promise [17].

## Conclusions

CHRIIS offers an effective remote tetherless supervised autonomy framework for inspection and light intervention of offshore marine assets. Leveraging on key emerging technologies such as 3D computer vision, mixed reality, digital twinning and machine learning, coupled with significant advances in robotics, automation, sensors, and communication, CHRIIS has to potential to provide better operational risk management and improving the overall HSE standards in offshore IRM operations.

## Acknowledgments

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## Nomenclature

*CHRIIS* - Collaborative Human Robot Inspection & Intervention System
*ROV* - Remotely Operated Vehicle
*AUV* - Autonomous Underwater Vehicle
*HUV* - Hybrid Underwater Vehicle
*TMS* - Tether Management System
*IRM* - Inspection, Repair & Maintenance
*OSV* - Offshore Support Vessels
*FEC* - Forward Error Correction
*HSE* - Health, Safety & Environment

## References

[1] Fortune Business Insights, “Offshore Inspection, Repair & Maintenance Market Size, Share & COVID-19 Impact Analysis, and, Forecast 2021 - 2028.” https://www.fortunebusinessinsights.com/inspection-repair-and-maintenance-market-102983

[2] A. Shukla and H. Karki, “Application of robotics in offshore oil and gas industry— A review Part II,” *Robotics and Autonomous Systems*, vol. 75, pp. 508–524, Jan. 2016, doi: 10.1016/j.robot.2015.09.013.

[3] D. A. Anisi and C. Skourup, “A step-wise approach to oil and gas robotics,” *IFAC Proceedings Volumes*, vol. 45, no. 8, pp. 47–52, 2012, doi: 10.3182/20120531-2-NO-4020.00022.

[4] J. G. Bellingham, “Platforms: Autonomous Underwater Vehicles,” in *Encyclopedia of Ocean Sciences (Second Edition)*, J. H. Steele, Ed. Oxford: Academic Press, 2009, pp. 473–484. doi: 10.1016/B978-012374473-9.00730-X.

[5] J. H. Vincent, N. D. Sevinc, and N. A. Herbst, “uROV – The Next Generation IMR Platform Utilizing Supervised Autonomy,” presented at the Offshore Technology Conference, Apr. 2019. doi: 10.4043/29586-MS.

[6] B. Johansson, J. Siesjö, and M. Furuholmen, “Seaeye Sabertooth A Hybrid AUV/ROV offshore system,” in *OCEANS 2010 MTS/IEEE SEATTLE*, Sep. 2010, pp. 1–3. doi: 10.1109/OCEANS.2010.5663842.

[7] A. D. Bowen *et al.*, “The Nereus hybrid underwater robotic vehicle for global ocean science operations to 11,000m depth,” in *OCEANS 2008*, Sep. 2008, pp. 1–10. doi: 10.1109/OCEANS.2008.5151993.

[8] J. E. Manley, S. Halpin, N. Radford, and M. Ondler, “Aquanaut: A New Tool for Subsea Inspection and Intervention,” in *OCEANS 2018 MTS/IEEE Charleston*, Oct. 2018, pp. 1–4. doi: 10.1109/OCEANS.2018.8604508.

[9] M. Chitre, S. Shahabudeen, and M. Stojanovic, “Underwater acoustic communications and networking: Recent advances and future challenges,” *Scopus*, Mar. 2008, Accessed: Oct. 12, 2020. [Online]. Available: https://scholarbank.nus.edu.sg/handle/10635/110914

[10] M. S. Martins, J. Cabral, G. Lopes, and F. Ribeiro, “Underwater acoustic modem with streaming video capabilities,” in *OCEANS 2015 - Genova*, May 2015, pp. 1–7. doi: 10.1109/OCEANS-Genova.2015.7271756.

[11] M. Rahmati, A. Gurney, and D. Pompili, “Adaptive Underwater Video Transmission via Software-Defined MIMO Acoustic Modems,” in *OCEANS 2018 MTS/IEEE Charleston*, Oct. 2018, pp. 1–6. doi: 10.1109/OCEANS.2018.8604782.

[12] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, “Underwater optical wireless communications, networking, and localization: A survey,” *Ad Hoc Networks*, vol. 94, p. 101935, Nov. 2019, doi: 10.1016/j.adhoc.2019.101935.

[13] A. Mahmood and M. Chitre, “Ambient Noise in Warm Shallow Waters: A Communications Perspective,” *IEEE*

*Communications Magazine*, vol. 55, no. 6, pp. 198–204, Jun. 2017, doi: 10.1109/MCOM.2017.1500617.
[14] M. Chitre, R. Bhatnagar, and W. S. Soh, "UnetStack: An agent-based software stack and simulator for underwater networks," 2015. Accessed: Oct. 12, 2020. [Online]. Available: https://scholarbank.nus.edu.sg/handle/10635/127689
[15] T. Waltemate *et al.*, "The impact of latency on perceptual judgments and motor performance in closed-loop interaction in virtual reality," in *Proceedings of the 22nd ACM Conference on Virtual Reality Software and Technology*, New York, NY, USA, Nov. 2016, pp. 27–35. doi: 10.1145/2993369.2993381.
[16] A. El. Gamal, J. Mammen, B. Prabhakar, and D. Shah, "Throughput-delay trade-off in wireless networks," in *IEEE INFOCOM 2004*, Mar. 2004, vol. 1, p. 475. doi: 10.1109/INFCOM.2004.1354518.
[17] A. Chaudhary, R. Mishra, B. Kalyan, and M. Chitre, "Development of an Underwater Simulator using Unity3D and Robot Operating System," in *OCEANS 2021: San Diego – Porto*, Sep. 2021, pp. 1–7. doi: 10.23919/OCEANS44145.2021.9706012.