In: 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 25-29 March 2023, Shanghai, China
DOI: 10.1109/VRW58643.2023.00089

Telexistence-Based Remote Maintenance for Marine Engineers

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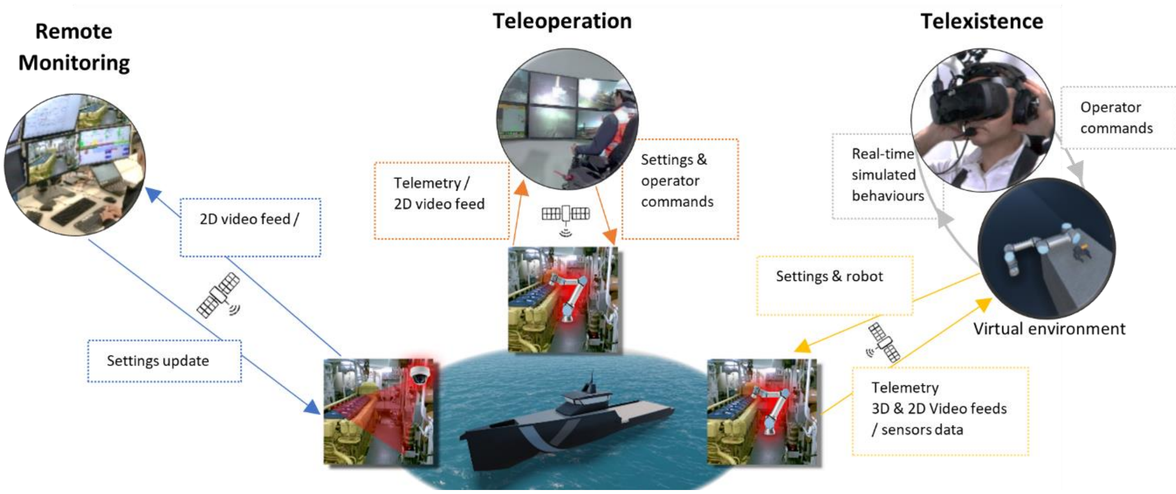

Figure 1: Remote maintenance solutions for the machinery space.

Abstract

Remote work practice has seen significant developments in the field of maintenance, which is beneficial in the maritime sector. The defense industry is investigating the utilization of unmanned vehicle systems (UVS) to fulfil the demands of efficiency, safety, and field tasks that heavily rely on equipment usage. Telexistence technology affords marine engineers the capability to conduct inspections and repairs as if physically present. This study presents a scalable framework for evaluating the feasibility of conducting traditional machinery space maintenance through the implementation of telexistence capabilities. Our case study employs a physical robot for real-motion behaviors and a simulated virtual environment. Maintenance scenarios were developed through responses to a contextual questionnaire by two experts. In future steps, the study will compare telexistence with direct teleoperation in terms of presence, workload, and usability for vessel machinery space maintenance.

Index Terms: Virtual Reality—Remote Control—Human-Robot Interaction— Telexistence—Maintenance

1 Introduction

The maintenance of a vessel's machinery space usually involves a series of activities conducted by marine engineers [1], [2]. Remote maintenance has the potential to improve the efficiency and safety of maintainers in charge of unmanned ships. In addition, it can also reduce the time and cost associated with maintenance, as the maintainer can perform multiple tasks simultaneously and does not need to travel to the ship. The defense sector is showing great interest in the deployment of UVS [3] to limit the use of human resources in hostile operational environments, but UVS must be maintained. The remote maintenance solution should try to reduce the hours dedicated to maintenance and make it more effective.

Current remote maintenance relies on remote monitoring and teleoperation (**Figure 1**).

Remote Monitoring: This approach entails the use of sensors and other equipment to gather data on the condition and performance of the machinery space, which is then transmitted to a remote location for analysis and monitoring. However, it provides a limited representation of the actual environment and anomalies such as smoke or heat can be challenging to visualize. Although it is an effective condition-based maintenance strategy, it is limited in terms of corrective action as complex issues may necessitate the physical presence of maintenance personnel.

Teleoperation or Direct teleoperation: This approach involves using remote control systems to operate and manipulate equipment and machinery in the engine room [4]. It enables maintenance personnel to perform tasks such as turning valves or starting and stopping engines without being physically present in the engine room. The effectiveness of the teleoperation interface relies on the maintainer's ability to operate the equipment. However, currently, teleoperation interfaces can be complex and challenging to use, especially for tasks that require a high degree of dexterity and accuracy, making it difficult for the maintainer to perform maintenance tasks efficiently and accurately [5]. One of the major challenges of remote maintenance is the potential for technical errors or mistakes as maintainers may not have the same level of physical access and control as they would have when working on-site. This can result in incorrect diagnoses or repairs and require additional time and resources to rectify.

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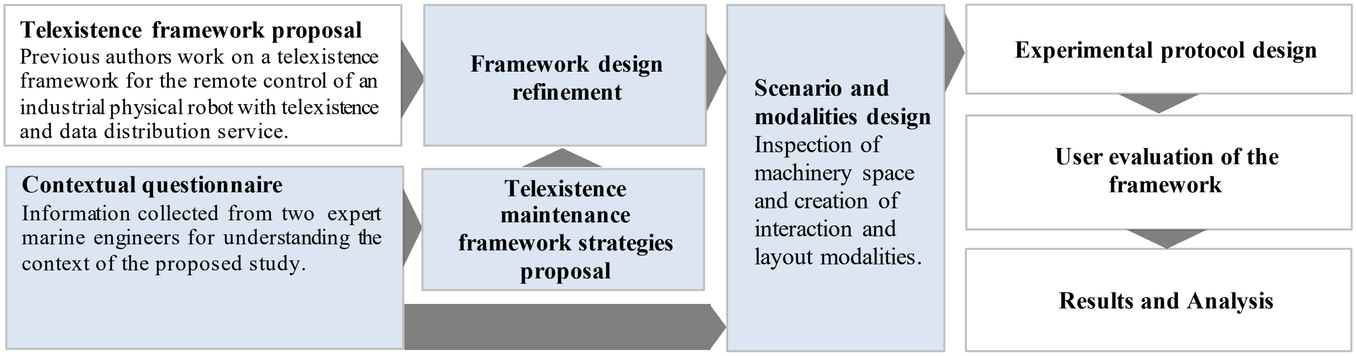

Figure 2: Overview of methods used for developing and evaluating the telexistence framework for maintenance. The topics covered in this paper are in light blue.

To address these challenges, telexistence capability [6] can provide an appropriate level of presence in the machinery space through a virtual environment with the digital twin (DT) of the machinery space and the robot. DT refers to a virtual representation of real-time data on board. Telexistence creates a safe simulated virtual environment, linking the maintainer with a virtual reality (VR) head-mounted display (HMD) to the remote physical robot performing the task. This approach should not lead to cognitive overload for the maintainer or a low sense of presence, which could result in inefficiency or risks, as the maintainer would forget that he/she is operating a real robot at a distance. This study presents telexistence as a solution for conducting maintenance tasks and proposes a framework for evaluating and integrating telexistence-based remote maintenance procedures on board a ship with a limited crew or no crew. We examine various cases of telexistence integration and focus on one of them to design an experiment in ship machinery spaces.

2 Project Overview

A telexistence interface is proposed as a solution for the remote maintenance of unmanned and autonomous vessels by marine engineers. Current human-robot interaction strategies are limited, causing an impact on collaboration and efficiency. Telexistence, or virtual existence in a remote location, offers a safer and more effective alternative to remote monitoring and direct teleoperation. Before real integration onboard the vessel, maintenance tasks must be evaluated in a safe environment for the machinery space, robotic assets, and operators. A telexistence framework is proposed to assess and validate traditional marine engineering maintenance procedures. The goal of the telexistence interface is to enhance the sense of presence while breaking down geographical barriers.

2.1 Method

The proposed method in **Figure 2** designs a framework and use case for the evaluation of maintenance tasks using telexistence. Firstly, a framework for remotely controlling industrial arms with telexistence capability has been proposed as a starting point for this study. Information on machinery space maintenance was obtained through a contextual questionnaire given to two industry experts. The responses identified the challenges faced by marine engineers and provided strategies for implementing telexistence. A maintenance scenario was created for the evaluation of the framework, and an experimental protocol is planned to assess its effectiveness in conducting maintenance tasks using an interface with telexistence capability in comparison to direct teleoperation. The results will be analyzed to validate the feasibility of telexistence for machinery space maintenance.

2.2 Telexistence

The authors aim to integrate telexistence with maintenance tasks through a machinery room inspection study. The desired long-term features will support a diverse range of inspection and repair tasks, provide operator guidance, accommodate diverse types of robotic systems, facilitate interactive DT, semi-automatically label faults, and adapt its user interface dynamically based on the task context. These features aim to aid marine engineers in conducting remote maintenance and sharing inspection reports with ship owners, operators, and manufacturers. Telexistence was first proposed by Professor Susumu Tachi in the 1980s [6]. As related technologies in areas such as robotics and immersive technologies became more accessible [7], researchers started exploring telexistence potential for various applications, such as remote control of industrial equipment, remote exploration of hazardous environments, and telemedicine. Telexistence requires a robotic system, sensors, a gateway, network platforms, a user interface, and an operator [8], [9], as shown in **Figure 3**. The central concept of telexistence is "presence" in a virtual environment, which refers to an interactive computer-generated environment created by a VR system [10]. The level of immersion and presence experienced by the user depends on the hardware and software used, including the choice of devices and the design of the interface.

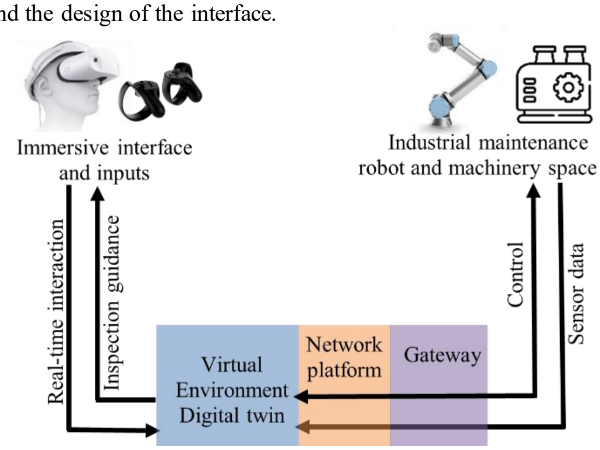

Figure 3: General elements to implement for telexistence maintenance.

2.3 Project contributions

This paper proposes a telexistence-based framework for evaluating and validating the feasibility of conducting maintenance tasks aboard a vessel using telexistence technology, with the same results as traditional methods. The authors present two contributions:

- The design of a scalable telexistence framework for machinery space maintenance task assessment and validation.
- The design of an engine part inspection use case, and the experiment protocol setup to evaluate direct teleoperation and telexistence.

The framework is based on a previous architecture by the authors using a physical FANUC[1] industrial robot [11] and demonstrates its scalability to new robots. With the right level of situational awareness and immersive DT technology available on modern vessels, it is hypothesized that many traditional onboard maintenance tasks can be performed with greater efficiency using telexistence compared to remote monitoring and direct teleoperation (**Figure 1**).

2.4 Understanding the context

Two experts, a 49-year-old marine engineer with 31 years of experience and a 59-year-old marine engineer with 37 years of experience, were asked to complete a contextual questionnaire to enhance the author's understanding of vessel maintenance. The questionnaire consisted of twelve questions focused on the job and activities of marine engineers and aimed to reflect on future working interfaces. The following summarizes the key points that informed our framework development and maintenance scenario creation:

Day-to-day job:
The daily responsibilities of marine engineers involve reporting overdue maintenance items to the marine engineering department and coordinating with the command for machinery shutdown. Using logged machinery performance data and observations from watchkeepers, they detect imminent failures or systems that require further investigation.

Common maintenance tasks:
Common maintenance tasks in the machinery space include daily inspections, data logging if not recorded automatically, cleaning, tightening connections, replacing gaskets, and routine oiling and greasing.

Diagnose onboard the vessel:
Troubleshooting onboard is performed using watchkeeping senses such as sound, sight, smell, and touch. Engineers also utilize condition monitoring techniques like vibration analysis and oil analysis to diagnose problems.

Safety:
Safety in the machinery space is maintained through measures such as tracking personnel with identification discs, implementing the buddy system, which is never alone in the operating area, and wearing personal protective equipment including fire-resistant clothing, ear protection, and steel-toed safety boots. Hazards such as hot surfaces and slippery decks should also be considered before conducting the work. Extra precautions as well if the ship is maneuvering or in a high sea state.

Training:
Marine engineers receive training through a combination of shore-based instruction and onboard mentorship. Task books are used to record the completion of necessary activities.

Main challenges:
Challenges in marine maintenance include understanding the design intent, system-based fault finding, and determining the material state.

Maintenance differences across different vessels:
Maintenance practices vary between naval and non-naval vessels, with the priority being the safety of personnel on civilian vessels and mission continuation on naval vessels.

Design of the maintenance user interface:
First, the presentation of the priority of alarms; Current systems presents alarms and warnings as they are interrogated by the system. This results in a mass of alarms that you cannot see, and the alarm order does not reflect how the fault occurred. Secondly, to give the user the right information, when they need it, in a format they can use. It might take a while for users to gain confidence in the system, so it must be as useful and correct as possible before being rolled out to sea. Also, as the amount of data being produced by systems on naval vessels go up dramatically, the data needs to be processed and presented to the user without drowning them.

Envision of future maintenance practices:
- Providing technical information at the point of work.
- Condition monitoring that interventions to prevent failure as opposed to telling you why something has failed.
- Subsystem DT at a sufficient level to allow both warnings of imminent failure or issues, and conduct 'what if' games to see the effect on system performance and failure of proposed operations, operating regimes, and profiles.

Envision of the future user interface:
- Provide automatization to remove the need to do mundane tasks, there should be no need for manual recording of running parameters at the machine for example.
- Overlay running parameters on a view of a machine; enhance with analysis e.g., where is this pump on its pressure/flow curve and what is its performance trend.
- Present known defects and allow new ones to be added e.g. leaks.
- Material state information – more for maintainer/supervisor e.g., latest condition monitoring results, when last run for standby machinery.
- The provision of operational guidance to a platform while underway, in peacetime and wartime conditions, via awareness of expected versus actual Hull, Mechanical and Electrical (HM&E) system performance, likelihood of what system failures with different operating profiles.

In conclusion of this section, telexistence has the potential to enhance remote maintenance for vessels with limited crew at various levels. The marine machinery space poses dangers to marine engineers and requires advanced training, but telexistence offers a safer alternative through immersive virtual environments with user-friendly interfaces. Furthermore, experienced marine engineers can offer their skills from any location, while VR-based interfaces can address the need for specialized marine maintenance knowledge and procedures, as interactive cues overlap immersive models to assist the user [12] and subsequently increase efficiency in task prioritization. With the advancement of interfaces, telexistence may eventually provide a multi-sensory environment to simulate the senses used in watchkeeping and problem-solving by marine engineers.

3 TELEXISTENCE MAINTENANCE FRAMEWORK STRATEGIES

The concept of telexistence involves the use of a virtual environment that provides a safe simulated 3D space, addressing the safety issues faced by marine engineers. The virtual environment is augmented with sensor information to enhance the

[1] https://www.fanuc.eu/

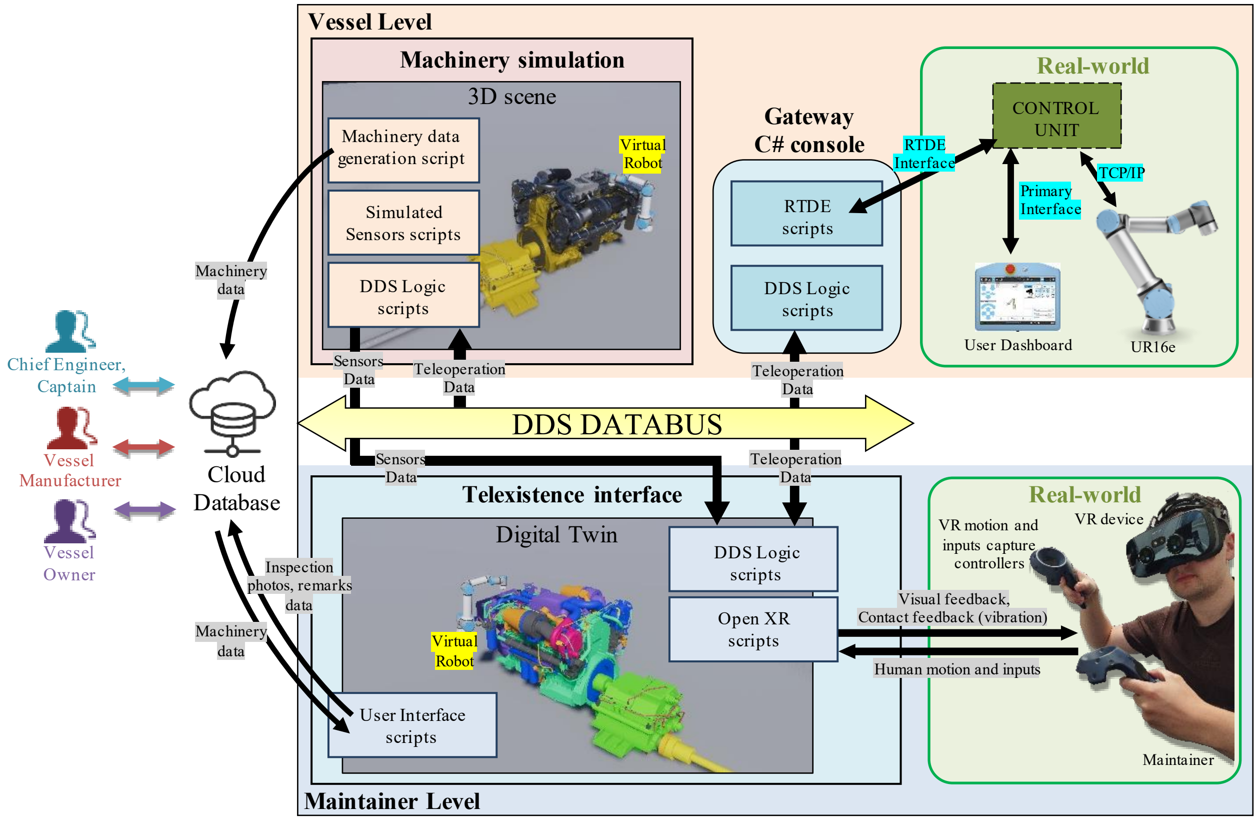

Figure 5: High-level system architecture and data flow overview.

user's awareness. Telexistence activates the senses of marine engineers who rely on their senses to troubleshoot problems from a distance by selecting the appropriate hardware, intending to create the sensation of being in another place. There are two types of telexistence: standard and augmented. Standard telexistence replicates the presence of a maintainer in real-time or with minimal delay using a surrogate robot [13] with similar visual and sensory capabilities as a human. Augmented telexistence aims to enhance the maintainer's capabilities for tasks that require abilities beyond human capability or in situations where real-time communication is not possible, such as high sea state. Moreover, this also includes situations when the distance or network does not allow real-time communication between the maintainer and the robot, e.g., high sea state. Augmented telexistence can be applied in maintenance using advanced sensors, such as thermography sensors, to extend human sensory experience and cognition. Integration of telexistence into maintenance can be achieved through various strategies, as depicted in **Figure 4**.

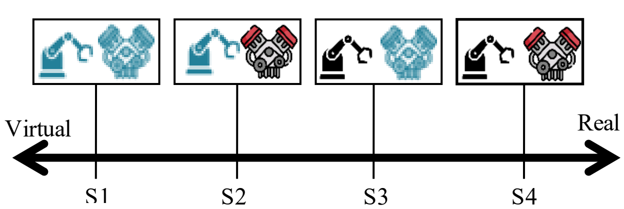

Figure 4: Telexistence maintenance strategies levels.

S1: Simulation in the engine room with the offline robot programming tool, to be implemented in a test context when no telexistence robot is available on board the vessel.
S2: Uses the real machinery space and when sensors data are available, with the offline robot programming tool. Can be implemented as a tool for choosing the telexistence best suitable for the vessel machinery space layout.
S3: Preparation of motion planning in a simulated environment before sending the command and maintenance program to the robot. It uses the motion behaviors of the real robot to maintain the accuracy of real-world conditions.
S4: Integration of the telexistence robot into the physical machinery space, as the tasks have been previously evaluated and are ready to be performed by the marine engineer at a distant location with a sufficient level of telexistence.

4 Framework Development

Figure 5 describes the elements implemented in our telexistence framework at the vessel and maintainer levels, we based our framework on the **S3** in **Figure 4**. The protocol allowing communication between both is DDS[2] (Data Distribution Service). It is a messaging standard for real-time systems that are designed for data-centric publish-subscribe applications. It is typically used in applications that require low-latency, high-throughput communication of large volumes of data, such as in control systems, robotics, and the Internet of Things (IoT). The DDS protocol allows for decoupled communication between publishers and subscribers, enabling distributed systems to exchange data without the need for a centralized component or intermediary. The

[2] https://www.dds-foundation.org/

DDS protocol facilitates communication and coordination between the various components of a telexistence system, such as the remote robot, the VR interface, and the DT interface. For example, the DDS protocol is used to publish sensor data thanks to the gateway from the robot and subscribe to commands from the maintainer, allowing real-time, bi-directional communication between the remote robot and the maintainer.

DT technology can be used in conjunction with telexistence to provide a more realistic and immersive experience for the maintainer controlling the remote robot [14]. A DT is a virtual representation of a physical object or system, which can be used to simulate and analyze its behavior and performance [15]. In the context of telexistence for remote maintenance, a DT of the remote robot can be created and used to provide real-time feedback and data on the movements and position of the robot regarding the engine room environment. This can be displayed to the maintainer controlling the robot, allowing them to better understand the remote environment [16]. Additionally, the DT of the robot helps to simulate potential scenarios, allowing the maintainer to evaluate different actions and strategies without physically affecting the remote robot. This is particularly useful for training and testing purposes, as well as for making more informed decisions about how to operate the robot in a remote environment.

In our framework **Figure 5**, the marine engineer uses the machine space of the DT vessel and the DT telexistence robot to operate the latter. He takes advantage of the CAD models of the asset to be inspected with combining the RGB camera sensors and the available data. We are simulating a marine diesel engine and generating synthetic data to emulate a maintenance scenario. The data can be made available to the chief engineer and captain, the vessel manufacturer and the vessel owner through a cloud-based database and web interface. The telexistence interface displays the data in an immersive and interactive virtual environment for the maintainer. Finally, the maintainer can report and store maintenance reports, including inspection photos, in the database so that they can be accessed by the relevant stakeholders.

4.1 Vessel level

On the vessel level, the proposed framework is based on a universal robot[3] arm UR16e. It is a collaborative robot, also known as a “cobot,” designed for use in manufacturing and production environments. It can adapt to different situations and could be provided as a telexistence robot dependable enough for marine environments. It has a payload capacity of sixteen kilograms and a reach of 930 millimeters, making it suitable for assembly and materials handling. The robot includes a set of safety features such as collision detection and force control. For the maintenance context of machinery space, a 3D scene built on Unity 3D[4] game engine is developed and in charge of creating data for the simulation and testing of the maintenance tasks. It is a tool for creating 2D and 3D interactive content and offers features such as a physics engine, 3D animations and a wide selection of tools and assets for creating virtual environments.

4.2 Maintainer level

On the maintainer level, the operator of a VR HMD is using an HTC VIVE Pro[5] which features a pair of high-resolution AMOLED displays and built-in sensors such as gyroscopes and accelerometers to track the user’s movements and orientations. The user interface application is running on a suitable computer and has been developed using the game engine Unity 3D.

5 MAINTENANCE SCENARIO CREATION

To assist the evaluation of our proposed framework we have designed a task that the marine engineer could do in the machinery space. The task will be done with a real robot but under simplified conditions, as we do not have easy access to a real machinery space. The scenario is described in **Figure 6**.

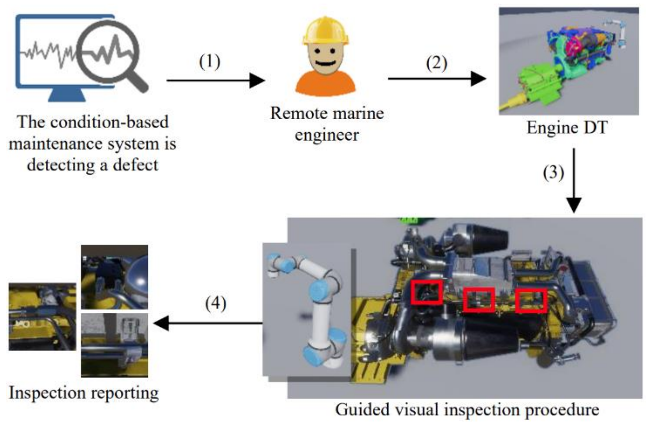

Figure 6: Inspection scenario.

(1) The condition-based maintenance system is detecting a leak and requested an operator to inspect three areas of the engine to locate the leak.
(2) The remote marine engineer is using the telexistence framework to immerse himself in the DT and take control of the inspection robot.
(3) A guided inspection procedure is displayed to the user for him to move the robot equipped with the camera.
(4) The image data are recorded and transmitted to the marine engineering department for quick and safe decision-making.

Our framework presented in **Figure 5** will serve as a virtual test bed for the validation of the proposed maintenance inspection scenario. It applies the **S3** in **Figure 4** before integration as the **S4**. The use of a physical robot in **Figure 7 (A)** allows for the simulation of real behaviors. The use of a simulated machinery space in **Figure 7 (C)** mimics the unmanned vessel for a safe assessment of the maintenance procedure. Communication is done using the gateway console application developed as a part of this framework in **Figure 7 (B).** The framework aims to provide a report of the inspection (e.g., photos, times, and maintainer remarks) thanks to the telexistence user interface features in **Figure 7 (D).**

This framework has limitations as we are conducting the study under simplified conditions. We do not consider connection and latency issues. Poor network connectivity is likely to occur in high-seas environments and may lead to disruptions in data transmission. Furthermore, the chosen universal robot may not be the most suitable for the machinery space layout assessed. Either a refinement of the design of the machine space or the testing of other telexistence robots should be considered. However, our proposed DDS-based framework is highly scalable and can be adapted to other robots.

[3] https://www.universal-robots.com/

[4] https://unity.com/

[5] https://www.vive.com/

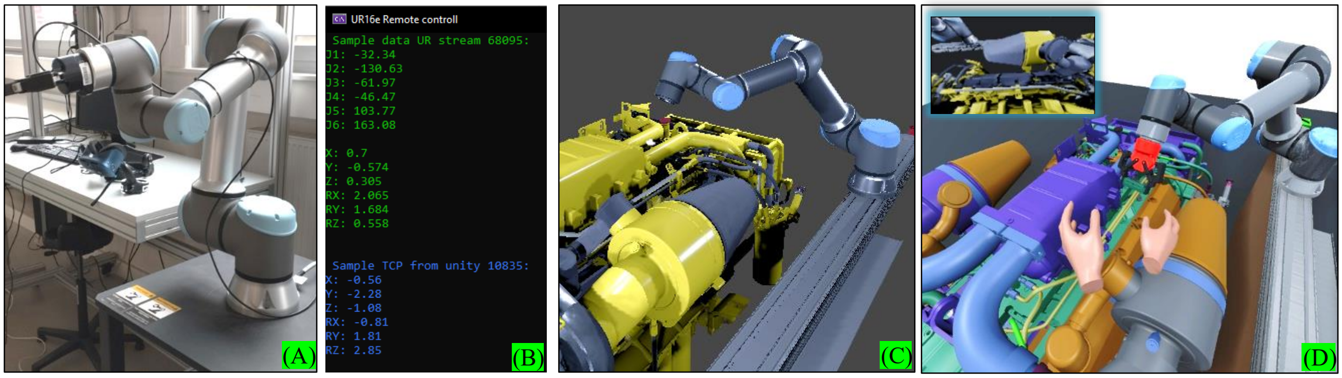

Figure 7: Proposed telexistence framework for the evaluation of vessel maintenance tasks, (A) physical robot, (B) C# console gateway application, (C) machinery space simulation, and (D) telexistence user interface.

6 FUTURE WORK

The purpose of this study is to compare and evaluate telexistence and direct teleoperation for vessel machinery space maintenance. Both modalities have been developed in Unity 3D, and robot inverse kinematics are computed directly within it[6]. The first modality will be to use direct teleoperation using a 2D screen, mouse, and keyboard, with a user interface that provides two camera views. The second modality will be to use the telexistence capability through our proposed framework (**Figure 5**), providing the user with enhanced visualization and immersive assistance toolsets to operate the physical robot safely and perform the maintenance task.

Based on our proposed study, we hypothesize that a telexistence framework for remote maintenance of unmanned vessels enhances presence and ensures the effectiveness of task performance. Thus, interaction with the telexistence robot is a crucial aspect of the framework to consider for providing the appropriate level of presence. This study aims to address the following hypotheses:

1) The comparison between direct teleoperation and telexistence interface reveals the following benefits in favor of the telexistence maintenance strategy:
    a. Enhanced situational awareness.
    b. Decreased number of incorrect movements.
    c. Improved task performance.
    d. Reduced workload.
    e. Improved usability.
2) The implementation of a virtual telexistence robot enhances the user's sense of presence through its user-friendly interaction and seamless path-planning programming.

An experimental protocol is designed to evaluate the framework with a user study. We want to record user performance data including time to 1) complete the task, 2) quality of the inspection performed (inspection photos taken), and 3) the participant number of collisions (e.g., the robot is going to hit the environment/is out of range). Through questionnaires, we want to study the human factors of, presence, workload, and usability. Finally, the following statement questionnaire will be given to the participant to give feedback on whether they agree or not using a five-level Likert scale and evaluating factors of physical space, engagement, and naturalness [17].

1. It felt like I was moving into the virtual world.
2. I had no problem keeping my concentration throughout the experiment.
3. It felt realistic to be in the virtual world.
4. It was easy to understand the robot's intentions and where it was going to move.
5. The robot felt safe to work with.
6. It was easy to perform the remote inspection with the robot.
7. It felt like my behavior in the virtual world was the same as my behavior in the real world.
8. I think a virtual environment like this is good for working remotely.
9. I felt like I was playing a video game rather than using remote maintenance inspection software.

7 DISCUSSION AND CONCLUSION

Telexistence can be an excellent solution for remote maintenance activities, especially on UVS in the naval sector. In principle, a telexistence system can be equipped with sensorial devices including vision, audio, and touch. The current state of telexistence is an area of advanced multidisciplinary research and is expensive. The current hardware sensors, robotic systems and immersive devices still need to be improved, especially in terms of ergonomics for real-world usage implementation. For instance, advanced control systems like haptic gloves providing force and touch feedback are complex to fit, heavy and cumbersome to be integrated with a real use case.

However, telexistence has much to offer and can overcome the example of communication and connectivity issues. If the communication is offline, future maintenance tasks can be prepared and, when it is re-established, data and commands can be sent and received. Moreover, an immersive real-time environment can provide an efficient way of displaying dynamic user interfaces that adapt themselves to the context of the task, environment (in peacetime and wartime conditions, offshore or docked) and operator knowledge.

This paper aims to provide an overview of how telexistence could be integrated as a strategy for remote machinery space maintenance for future intelligent unmanned vessels. While most of the studies focus primarily on the means of interaction of VR-based telerobotic, only a few focus on contextual use case studies. We have refined our previously developed framework to use it as a tool for maintenance task validation before real integration onboard the vessel. In future steps, we will evaluate the framework through the

[6] https://www.youtube.com/watch?v=9upypT6OWwk

maintenance scenario outlined in Section 5 and compare direct teleoperation and telexistence to perform the maintenance.

ACKNOWLEDGMENTS

This research is funded by the joint Anglo-French PhD scheme, organized by the respective nations' Ministry of Defense, with the Defence Science and Technology Laboratory (Dstl) acting as the Technical Partner.

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2023-05-01

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