Towards Reduced Human Intervention: Exploring Digital Twin and Mixed Reality for Inspection in Remote and Hazardous Environments

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Abstract

This report investigates the use of Mixer Reality (MR) and Digital Twin (DT) technologies to enable remote operations, inspections, and training for maintenance tasks and infrastructure that is access challenged or hazardous such as offshore windfarms or nuclear facilities. Through the integration of a ground robot equipped with sensors, HoloLens device, and digital twin models, a proof-of-concept system was conceived that enabled visualisation and control of the robotic platform. The methodology describes a framework for deploying mixed reality applications at different levels of the Reality-Virtuality (RV) continuum. This is implemented trough the fusion Clearpath's Jackal robot, HoloLens 2, ROS middleware, and the Unity platform. The robot streams real-time sensor data into the Unity environment which can be use for Augmented Reality (AR) or projected into Virtual Reality (VR) to create an Augmented Virtuality (AV) remote environment. With these three possible environments, three tasks are designed to demonstrate the utility of the framework. Based on a set of heuristics, scenarios were used in a user-study to evaluate, the mini-map, visualisation, user interface and navigation. The prototype demonstrates the potential of these technologies to transform inspection and maintenance practices by improving perception, reducing risks, and lowering costs associated with inspection and maintenance in offshore windfarms and nuclear plants. However, there remain significant technical obstacles around issues such as networking, interface design, digital twin fidelity, and autonomous capabilities. Extensive future research across disciplines including robotics, computer vision, and human factors is required to realize robust real-world implementations. While promising, this project revealed the complex integration challenges combining digital twins, augmented/virtual reality, and advanced robotics for next-generation inspection and maintenance solutions.

Keywords *Cyber-Physical Systems, Digital Twin, Extended reality, Human in the loop, Human-robot interaction, Heuristic Evaluation, Inspection, IoT, Robotics, Teleoperation*

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Table 1: Nomenclature

Abbreviation	Definition
AGV	Autonomous Ground Vehicles
AR	Augmented Reality
AV	Augmented virtuality
BVLOS	Beyond Visual Line Of Sight
DD	Digital twin Data
DT	Digital Twin
FMCW	Frequency Modulated Continuous Wave
HMD	Head-Mounted Display
HHD	Hand-Held Device
HRI	Human-Robot Interaction
IoT	Internet of Things
LTS	Long Term Support
MR	Mixed reality
MRTK	Mixed Reality Toolkit
O&M	Operation and Maintenance
PE	Physical Entity
RV	Reality-Virtuality
SSOSA	Symbiotic System Of Systems Approach
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
URDF	Unified Robot Description Format
VE	Virtual Entity
V&V	Verification and Validation

1. Introduction

Inspection, maintenance, and repair is essential to ensure the operational requirements are maintained throughout several facilities[1, 2, 3, 4]. This often requires humans to conduct Operation and Maintenance (O&M) in facilities which have certain risks such such as offshore wind farms or nuclear facilities[5]. Offshore wind farms present risks such as working at dangerous heights, exposure to electrical hazards, adverse weather conditions, potential for falls and collisions, and inexperienced personnel[6]. Nuclear power plants require rigorous inspection and maintenance to ensure safe operation. Key risks that must be managed include radiation exposure, criticality, contamination, industrial hazards, fire, system integrity impacts, human errors, foreign material intrusion, and configuration errors[7]. Companies in both these sectors require comprehensive procedures, training, and protection, including having the proper PPE. In addition, this has associated costs in getting engineers offshore[8, 9] and into these dangerous environments. Service Operation Vessels (SOVs) are widely employed in the maintenance activities of offshore wind farms[10]. The duration of offshore stays for personnel working on SOVs can vary depending on the specific tasks and maintenance requirements. Typically, technicians stay in the vicinity of a wind farm for extended periods, often around two weeks[11].

Autonomous robots[12] capable of high-level decision making could provide a good alternative by assisting human operators remotely. Advances in Beyond Visual Line of Sight (BVLOS) technologies[13] ensures that these robots can be effectively monitored and controlled, even from vast distances, instilling trust in their deployment[14]. In combination with digital twin representation of the facility these autonomous platforms can assist an operator on the field and even allow them to control multiple robots simultaneously[15]. The knowledge of the system behaviour and the digital asset has additional benefits. Faults can be simulated in the system for training purposes[16, 17] not only improving the training but also removing the need to train operators on site[17]. Safety is increased as reliance on human operators in these challenging environments is no longer required.

Implementing high-level decision-making capabilities in robots can help reduce costs associated with deploying human personnel and improve overall efficiency[18]. Additionally, reducing the cognitive load[19, 20] on human operators can enable them to control more robots simultaneously[21], further enhancing productivity. Using robots in conjunction with a Digital Twin (DT), a robot with a LiDAR is well suited for a Verification and Validation (V&V) inspection task[22, 23]. This report investigates how to use DT technology to create scenarios for assisted inspection, remote inspection[24, 25] and inspection training with Mixed Reality (MR)[26, 27]. Increasing the effectiveness of Human In The Loop (HITL) robot interaction.

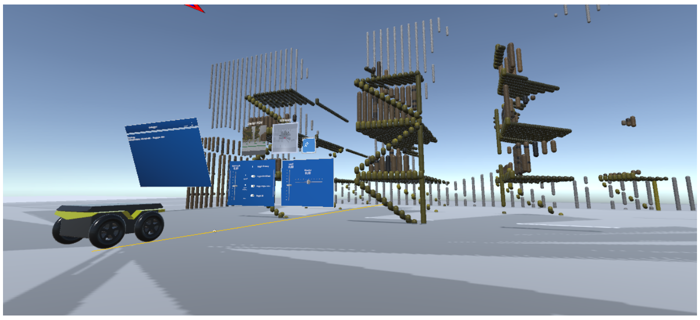

Figure 1: A video demonstration found on linktree and a link to the Project Github

In this project, components are developed to enable remote, assisted or training O&M of hazardous facilities using robotic platforms and mixed reality visualization. A ground robot is equipped with sensors to gather data about the environment. This data is streamed in real-time to a Head Mounted Device(HMD), where it is overlaid on a DT representation of the facility. The HoloLens[28] allows the operator to understand the context and control the robot.The system demonstrates capabilities for remote inspection, assisted on-site inspection, and simulation training scenarios by varying the level of immersion. These scenarios were performed by 4 participants that then provided feedback based on a set of heuristics. The implemented prototype revealed promising capabilities in enhancing human perception, understanding, and control as well as the reduction in human intervention for O&M tasks through the fusion of real and digital environments.

Compared to other state of the art solutions, this application provides a unique combination of remote and assisted inspection capabilities using an unmanned ground vehicle platform. It leverages augmented reality through the HoloLens 2 for on-site assistance, which is more advanced than solutions relying only on smartphones or tablets. The use of simulated environments also enables user familiarization prior to real-world deployment. However, technical limitations around networking, compatibility, and hand tracking may prevent the system from surpassing all cutting-edge solutions currently. Improvements in augmented reality technology and robot autonomy would further pave the way for more intricate and advanced applications in various domains. Integration of machine learning algorithms can enable the system to anticipate user needs, optimize the displayed information, and reduce cognitive overload. Furthermore, the synergy of HoloLens with the Clearpath Jackal robot opens up potential avenues for multi-robot cooperation, allowing for coordinated tasks and shared sensory data.

The report is organized into several key sections. It begins with a background section that gives an overview of the relevant concepts of digital twins, levels of robot autonomy, and reality . A literature review summarizes related work and industry applications in areas of robotics for inspection, augmented reality in maintenance, and digital twin technologies. The methodology section details the proposed system architecture, including the robotic platform, sensors, visualization device, networking, and software components used. This is followed by the implementation section which outlines the development process, including integrating the digital twin, building the augmented reality visualization in Unity, and networking the robot and HoloLens. The results present an evaluation of the system focused on assessing its usability and comparison to state of the art solutions. Finally, the discussion reviews the benefits and limitations of the approach, while the conclusion summarizes the contributions and potential impact of the research. Areas for future work are also proposed to build on the concepts demonstrated in this project. This structure provides context and rationale for the proposed solution, details the techniques used, and critically analyzes the end results.

2. Background

This section provides a comprehensive background on the underlying concepts pertinent to this study. Firstly, the concept of a Digital Twin (DT) is explored, highlighting its definition, importance, and required components for a successful DT implementation. The interaction between the Digital Entity (DE) and Physical Entity (PE) is emphasized, and their seamless integration in the cyber and physical spaces is illustrated with an example of the Clearpath Jackal robot's digital twin. Subsequently, human non-intervention is discussed in the field of robotics where its definition and importance are explained, along with its role in robotic safety and adaptability. Various levels of autonomy that gauge the degree of human involvement in robotic control are discussed. Different strategies and technologies aimed at reducing human intervention, such as the integration of context, Semantic SLAM, frameworks for moral decision-making in robots, and brain-computer interfaces, are touched upon. Next, the Reality-Virtuality (RV) continuum is introduced, which serves as a foundational concept for understanding virtual and augmented reality. This concept is discussed, the continuum's key zones—Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—are further elaborated upon, offering insight into their characteristics and distinctions. Finally, an description of cognitive load is made, discussing the detrimental impacts of high cognitive load on performance. The primary factors are explore, highlighting the significance of efficient human-robot interface design.

2.1. Digital Twin

Although this idea is not new, it remains a vague concept that encompasses a large variety of technologies and approaches[29]. The term refers to the digital replica of a physical entity, system or process[30]. The Digital Entity(DE) inhabits the cyber space and Physical Entity (PE) is in the physical spaces[31]. In general, a DT is defined as "The seamless integration between the cyber and physical spaces" [32]. Virtual representation of an object or system can be used to optimize and understand its physical counterpart[33]. Communication is usually bidirectional, where the physical asset is evaluated via sensors in real time and and digital twin is simulated[34].

When it was first introduced there were 3 required components: The digital representation of the asset, real physical asset, and the Information flow between these components[35, 36]. Other authors[37], have expanded this approach to include five components depicted in figure 2.1, these are as follows:

- **Physical Entity (PE):** Represents the tangible, real-world version of an asset or system. It's the actual physical counterpart that the digital twin mimics or simulates.
- **Virtual Entity (VE):** This is the digital representation or model of the PE. Depending on the complexity and the purpose, the VE can encapsulate various attributes such as geometry, materials, behavior, and more.
- **Services:** These encompass the processes, functionalities, or operations related to the digital twin. Services can range from operational tasks to analytical processes, aiming to both understand and optimize the performance of the PE.
- **DT Data (DD):** Captures all data linked with the Digital Twin. This can be static data, such as design specifications, or dynamic data like real-time operational statistics or performance metrics.
- **Communication:** Integral to the DT's operation, this ensures continuous bidirectional information flow between the PE and VE. Such communication can involve the transfer of real-time sensor data, feedback loops, or command updates, allowing for constant synchronization and optimization.

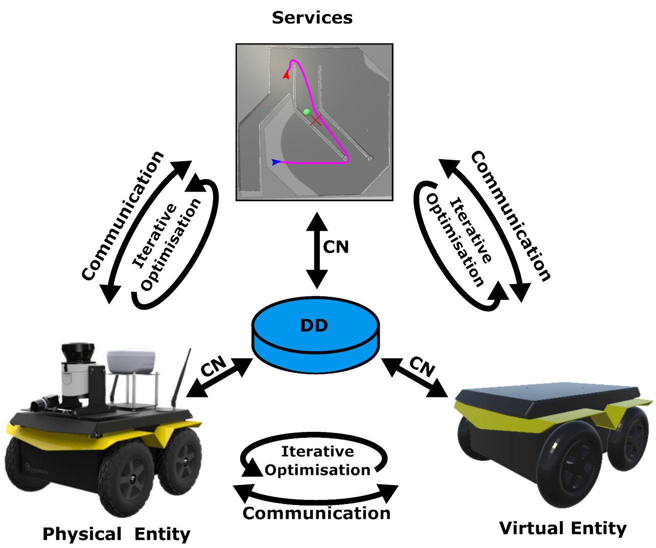

Figure 2: Jackal DT

2.1.1. Levels of Autonomy

The Six Levels of Autonomy provide a structured framework to gauge the human operator's involvement in controlling robotic systems[38].This framework is essential when considering how and when human intervention is required in various robotic tasks[39].

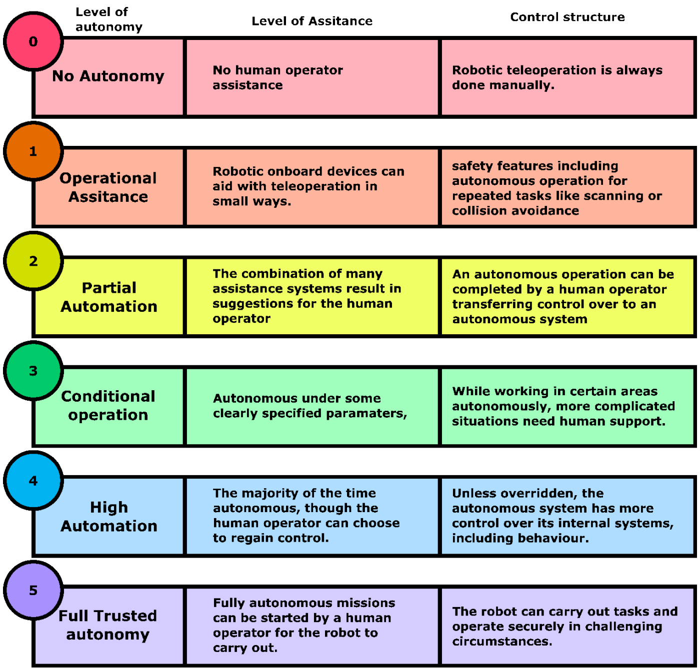

Figure 3: 6 Levels of autonomy[40]

2.2. Human Non-Intervention

Understanding the concept of human intervention in robotics is important, in robotics, this refers to the involvement of humans in the operation, control, or collaboration with robotic systems. This can range from direct control of the robot to goal-oriented supervision or even learning from human demonstrations[41]. The balance between human control and robotic autonomy is vital for safety, adaptability, and effective collaboration in diverse applications. By minimizing unnecessary intervention, we can reduce the operator's cognitive load, allowing focus on more advanced tasks.

Non-intervention in robotics is pivotal for numerous reasons. It promotes efficiency, allowing robots to operate continuously and at scale, and ensures safety by enabling robots to function in hazardous environments without human risk. This autonomy guarantees precise, consistent operations, especially in tasks requiring meticulous repetition. It also permits robots to operate in remote areas, offering economic advantages by reducing labor costs and allowing continuous operation. By automating routine tasks, humans can focus on more complex activities, fostering innovation. Furthermore, autonomous robotics drives advancements in AI and machine learning, benefiting the broader technological landscape.

The right balance between autonomy and interface design is dictated by the robot's capabilities, task intricacy, and the unpredictability of the environment. While fully autonomous manipulation remains a challenge in real-world unstructured environments, a certain degree of human intervention and teleoperation is indispensable. In many teleoperated systems, especially small unmanned systems with robotic manipulators, direct remote control by a human operator is preferred over full autonomy[42]. Physical devices, such as master-slave controllers and joysticks, provide intuitive manual control. However, they can be fatiguing over prolonged use. More autonomous devices, like computer workstations and tablets, offer advanced functionality but might compromise the intuitiveness of direct control. Visual enhancements using augmented reality, virtual reality, and stereo displays can boost operator performance and awareness. Yet, integrating information across different displays can be challenging. Haptic and force feedback, on the other hand, improve precision and force management. They can be supplemented with virtual fixtures to guide motion. However, these technologies demand a certain level of environmental and task understanding.

2.2.1. Methods of Reducing Intervention

Numerous structures and methods have been developed to reduce human intervention in autonomous and collaborative robotics. These include:

- Integrating Context[43]: By using artificial intelligence this research aims to fill in gaps to make effective decisions quickly supporting more robust behaviours. The robot can then suit the needs of the designated mission.

- Semantic SLAM[44]: This method integrates object recognition with traditional SLAM methods to create a semantic description of a scene. This enables robots to gain a better understanding of the environment to provide users with higher level assistance.

- Reducing moral ambiguity[45]: This introduces frameworks that enables robots to make moral decisions in human-robot interactions which could allow robots to have a lower reliance on the human operator when faced with such a decision.

- Brain-computer interface(BCI)[46]: By monitoring changes in brain activity, BCIs can estimate cognitive load, attention level, perceived errors and emotions. This information can be used to facilitate the interaction between humans and robots, enabling the interface to adapt to the users current state without the need for a human to prompt it to do so.

Human intervention in robotics is crucial for ensuring safety, adaptability, and effective collaboration between humans and robots in various applications. This can then reduce the cognitive load of a task to allow the operator to focus on higher level tasks. This is where MR can be used for intervention by an operator equipped with a intuitive control over a robot and a flexible level of autonomy.

2.3. *Mixed Reality*

Mixed reality[47] is a type of display on the RV continuum that combines real-world and virtual objects into and environment, allowing the user to interact with both[48]. This is a broader term that encompasses both AR and VR experiences.

2.3.1. *Definitions*

Virtual Reality (VR): This is a computer-Generated simulation of an environment. This can be interacted with in a seemingly real or physical way by a person using specialised equipment.
Augmented Virtuality (AV): This overlays real-world information in the virtual environment. Relying on information provided by sensors.
Augmented Reality (AR): This is a type of display on the RV continuum that combines virtual objects with real word objects in real-time, creating a mixed reality experience. By overlaying digital information on the user's view this enhances the users perception of reality.

The definitions provided some context for the Reality-Virtuality (RV) continuum that covers the 3 important aspects of creating a mixed reality experience.

2.3.2. *Reality-Virtuality continuum*

Introduced in 1994[49], the RV continuum, presented in figure 4 has been used as a framework for virtual and augmented reality development. This is a concept that describes different levels of immersion in virtual environments, which range from real world experience to completely virtual. With this, the three dimensions of the supporting taxonomy were introduced to describe the abilities of the visual display.

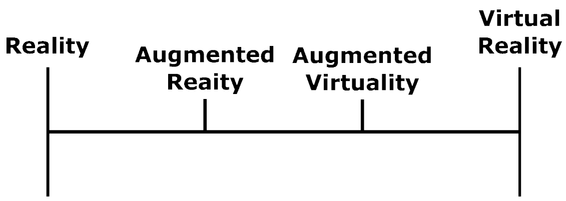

Figure 4: Virtuality, reality continuum

This has been revised ted numerous times as MR technologies have evolved over time[50]. The important elements are as follows:

Extent Of World Knowledge (EWK): This is what the information available about the world. This is collected via sensors. In the context of the Internet Of Things (IoT), the theoretical maximum EWK would provide all necessary information with no latency.

Coherence: This is the quality of the simulation. The more coherent the simulation is the more it is in tune with the real. This is often described by multiple mathematical models such as gravity, collision etc from a physics engine and a simulated controller. Figure 5 shows how increase coherence combines to make an ideal digital twin as all information of the system real and simulated is known.

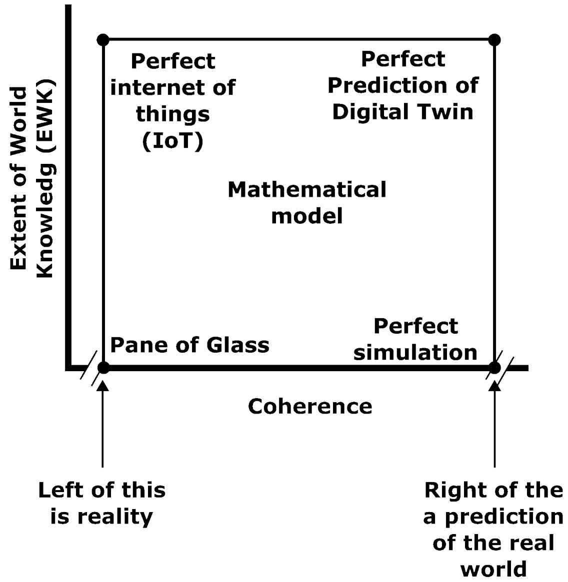

Figure 5: Extent of world knowledge coherence graph

Immersion: The level of immersion is the level on the RV continuum. This ranges form reality to AR where digital information is projected into the real world. This is followed by Augmented Virtuality (AV) where sensor information overlays a digital environment. The next stage is fully Virtual reality, where the user is fully in a virtual environment.

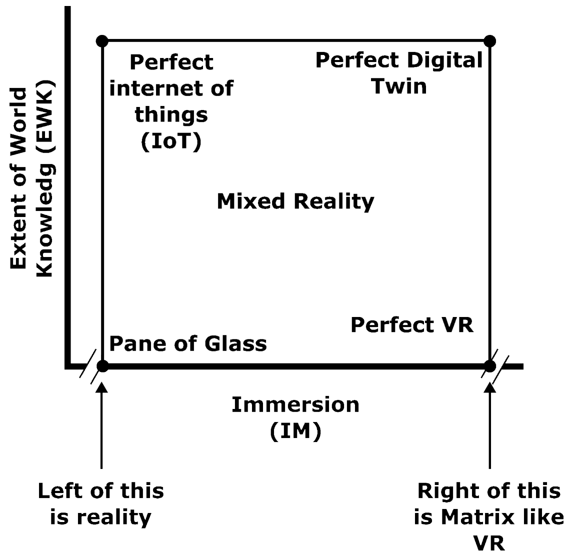

Figure 6: Extent of world knowledge coherence graph

Understanding these concepts provides context for the framework developed in the methodology. Since MR is a user-centred model of operation the user also needs to be considered. With a perfect EWK the risk of overloading the user with information can lead to decreased cognitive ability. It follows that minimising the cognitive load is crucial to maximise productivity as is expanded on in th following section.

2.4. Cognitive load

Cognitive load refers to the amount of mental effort required to complete a task. In the context of tele-operation, especially in challenging work environments[19], should not be overlooked. High cognitive load can degrade performance through increased errors, slower response times and narrowed focus, and fatigue, demonstrating the importance of designing human-robot interfaces that minimize unnecessary cognitive burden on operators[20].

The factors that influence cognitive load include:

- Complexity of controls
- Quality of visual/auditory feedback
- System lag
- Divided attention demands
- Poor ergonomic design

In synthesizing the advancements in the fields of Digital Twins, human-robot interactions, and the Reality-Virtuality continuum, this background sets the stage for convergence of these domains. At the heart of this project lies the interplay of digital representations and their physical counterparts, striving for seamless integration of cyber and physical. The understanding of varying levels of human intervention in robotics, from complete control to complete autonomy, reveals the potential and challenges in achieving safety, adaptability, and efficiency. RV continuum explores the use of Mixed Reality as an enabler of enhanced and immersive interactions for the control of robots.The emphasis on cognitive load acts as a constant reminder of the human-centred nature of this project, ensuring that any technological advancements or implementations remain user-friendly, intuitive, and efficient. This balance between technological sophistication and human-centered design is pivotal. It forms the basis for this project's journey into leveraging mixed reality and digital twins to revolutionize inspections and maintenance practices, particularly in remote and hazardous environments. With this foundation, the subsequent sections will delve into the detailed literature review discussing current industry practices and the state of the art.

3. Literature Review

This literature review explores the factors affecting the growth of digital twin and extended reality technologies by looking at trends, applications, benefits, and challenges. This will focus on use cases in nuclear facilities, offshore wind farms. Offshore oil rigs are also included as they also have access challenges, specialized protocols requiring diving operations and therefore a very specialised workforce.

The review begins with a quantitative analysis of the growth in publications related to these fields, clearly reflecting a growing interest and significant increase in research and development. It further delves into the core principles of Digital Twin Technology, exploring its integration in various sectors including utilities, manufacturing, energy, quality inspection, automotive, and industrial organizations.

Next, the review investigates how augmented and virtual reality technologies are being utilized for inspection and maintenance, outlining their potential to improve processes and detailing the hardware and technical limitations that currently challenge their widespread adoption. Specific attention is given to the novel concepts of Virtual Reality Remote Inspection (VRMI) and how digital twins are being leveraged in innovative ways for teleoperation, drone inspections, human-in-the-loop tasks, and more.

Lastly, the exploration of autonomous inspection frameworks introduces cutting-edge approaches like ultrasonic imaging technology, opening new horizons for automation and advanced inspections.

Overall, this review provides a comprehensive understanding of the state-of-the-art in the realm of digital twin and mixed reality technologies for robot collaboration, describing their potential and the hurdles that must be overcome. This literature review also highlights the interdisciplinary nature of this field, requiring collaboration across robotics, computer vision, human factors, and more, to realize robust real-world implementations.

3.1. Factors influencing DT, XR techonlogies and O&M

Using IEEE Xplore [51] a word search was conducted to find the main with the objective to find the overlap in these fields of robotics. The keywords used are Inspection, Digital Twin and Augmented reality.

Figure 7 shows a steady growth in Inspection and Augmented reality studies since 2006, increasing at a rate of an addition to 100 publications per year. Digital twin publications have increased by exponentially since 2016 with over 600 publications in this category per year.

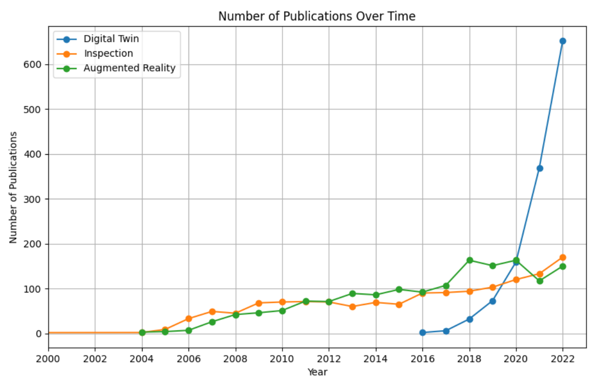

Figure 7: Publications per year

The most common phrases used in each category can be found in the appendix as well as word clouds C.45,C.46,C.47. This shows which Fields have the most involvement in each topic.

Inspection C.38, relates to words such as image processing, visual inspection, computer version. This outlines the need for a non-destructive methods of inspection.

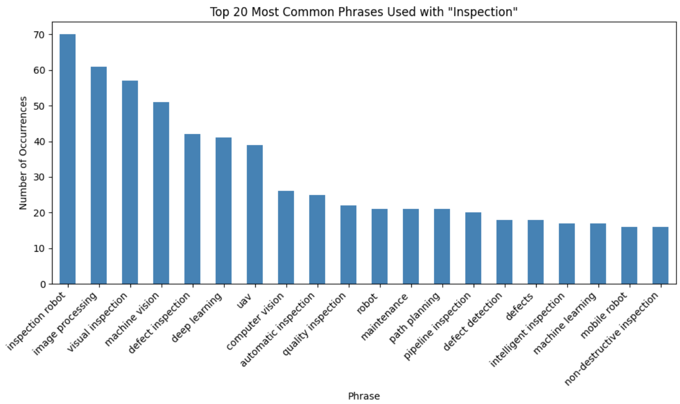

Figure 8: Top phrases associated with the topic "Inspection"

Digital twin C.39 relates to industry 4.0, Iot and cyber physical systems, which are integral to the creation, integration, and functionality of digital replicas of physical systems. The connection of digital twins to Industry 4.0 underlines its role in the next industrial revolution, where automation and data exchange are more prevalent.

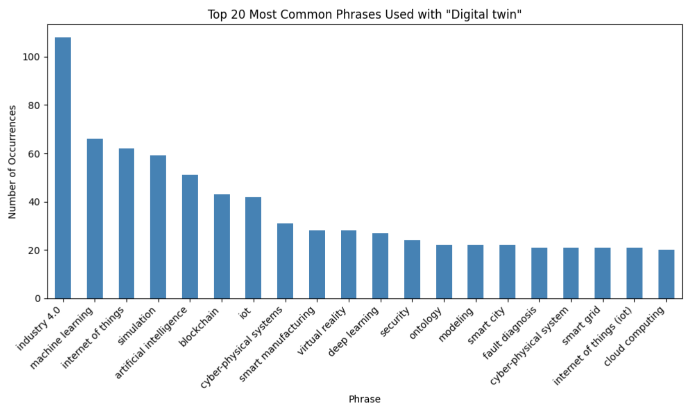

Figure 9: Top phrases associated with the topic "Digital Twin"

Augmented Reality C.40 has words such as human-centred computing, Human Computer Interaction(HCI), visualisation. These terms underline AR's focus on user-centred design and its capability to overlay digital content on the real world in an interactive manner.

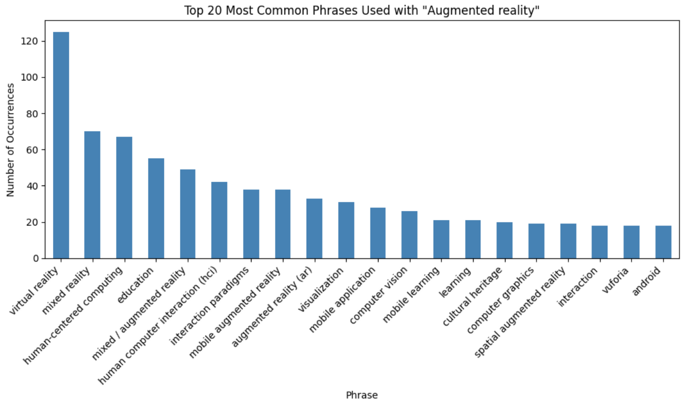

Figure 10: Top phrases associated with the topic "Augmented Reality"

Figure 11 shows the words that are in common with all three topics. The most common word is virtual reality, which was obviously present in AR but also very present in digital twin. Note that VR is not as present in Inspection which could show opportunity for an unexplored avenue.

Words like machine learning, deep learning, Artificial Intelligence, computer vision and neural network are also present. These are all examples of how to give systems additional autonomy. Rapid advances in the field of artificial intelligence could make digital twins very powerful and computer vision enables many new inspection capabilities.

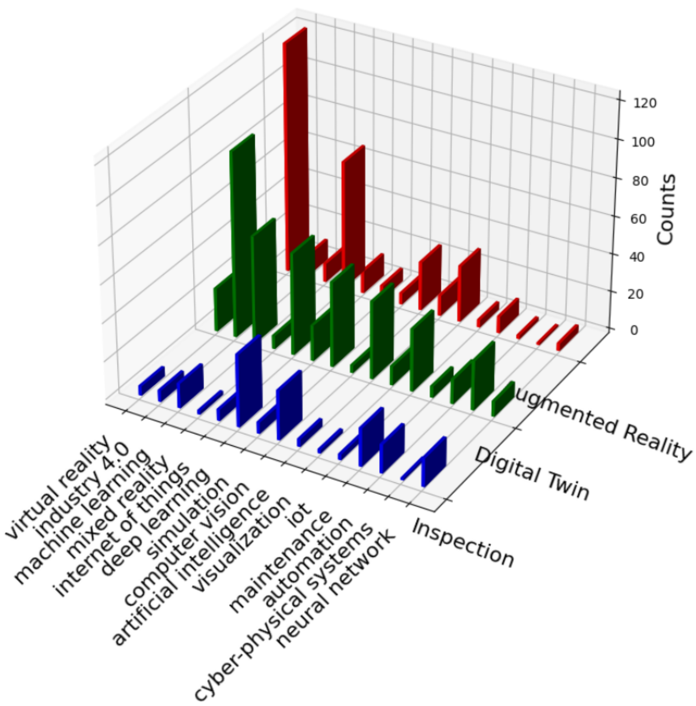

Figure 11: Most common phrases used by category

3.2. Digital Twin Technology in Industry

3.2.1. Foundations

The main foundations of DT technology comes from the study of production engineering, computer science and data science. The 4 most relevant parts are covered which are: service; data fusion;Simulation, modeling and verification, validation, and accreditation (VV&A) [37]; and Interaction and Collaboration;

1. **Service:** Service encapsulation[52], service matching and searching[53], quality of service (QoS) modelling and evaluation[54], service optimisation and integration[55], and fault-tolerance management[56] are all pertinent theories of service. By adopting a standardised information structure or interface, service encapsulation enables DTs to invoke various functionalities. DTs are able to select an appropriate service depending on customer requirements thanks to service matching and searching. DTs can assess the service quality using QoS modelling and assessment, which includes quantitative evaluation algorithms and dynamic updating methods. Finding the best service is made easier with the aid of service optimisation. Management of services that are fault-tolerant comprises fault detection, problem determination, and management strategy. The most appropriate service, such as maintenance, can be recommended to the client based on the service theories by DTs.
2. **Simulation, Modeling and VV&A:** DT modeling includes physical, virtual, connection, data, and service modeling. Physical modeling theories aid in capturing, defining, and articulating the core attributes of a PE. Theories of virtual modeling help create a digital replica of that PE, ensuring it emulates the same attributes and activities in a digital environment. This digital representation should ideally mirror its physical counterpart. Connection modeling theories aim to establish and sustain a seamless link among the physical, virtual, data, and service models. Such models typically cover aspects like data transfer, format transformation, and data source safeguarding. With data modeling theories, they guide the processes of data characterization, the definition of operational protocols (like security measures), and data archiving. They ensure that data is archived in a structured and logical manner, enhancing data handling. Service modeling theories offer insights into recognizing, examining, and refining services. Theories surrounding simulation are instrumental for operational assessments in simulated settings, such as evaluating structural integrity or motion dynamics. Lastly, VV&A ensures the accuracy of a digital model by inspecting potential errors in the model, algorithm, or hardware, thus providing a confidence measure in its validity.
3. **Interaction and collaboration:** To solve complex problems, all DT components must communicate and work together. DTs feature three different types of collaboration and interaction: virtual-virtual, virtual-physical, and physical-virtual. Multiple physical entities can communicate, coordinate, and work together to complete a complex task that is impossible for any one device to handle alone through physical-physical interaction and collaboration. Multiple virtual models can be linked together to create a network for information sharing through interaction and collaboration between other virtual entities. The virtual model can be improved in synchrony with the physical object through interaction and collaboration between the two, and the real object can be dynamically modified in response to direct commands from the virtual model.
4. **Data Fusion:** This involves three processes - data prepossessing, data mining and data optimization. DTs must first handle large amounts of data from both the VE and PE which needs to be pre-processed with methods including data cleaning, filtering and conversion. This data is then mined using methods such as rule-based reasoning, fuzzy sets or other data analysis methods. data optimisation is then used for dealing with iterations of the data to discover data evolution laws[57].

Industries	**Applications of Digital Twin Technologies**
Utility Companies	Locate potential leaks and reduce water loss with virtual simulations.
Manufacturing	Simulate the production process using data from IoT solutions, machine sensors, and manufacturing tools to create virtual representations of products, equipment, or systems.
Energy Sector	Evaluate operational opportunities, solutions to challenges, pricing, logistics, safety, hazards, and production optimization methods.
Quality Inspection	Enhance visual inspection processes (Example: Twyn, a mobile augmented reality platform for quality inspection, uses digital twins).
Automotive Industry	Ford develops seven digital twins for each model of vehicle it produces, each covering a different aspect of production.
Industrial Organizations	Digitize industrial assets, systems, and processes for better understanding, prediction, and optimization of industrial performance.

Overall DTs are commonly used in industry. This leads to a large amount of raw data as a consequence of simulation, modeling and VV& and aggregated data due to data fusion algorithms. This opens the door to visualising this data overlayed onto the PE in an immersive, more intuitive person so that it can be viewed and analysed by a human individual. This is where AR and VR can be leveraged to improve O&M as Human In The Loop HITL allow supervision of the DT.

3.3. Operations and Maintenance

As was seen in the previous section the DT can provide that data to improve AR and VR maintenance of facilities. This section covers the methods of using AR and VR to improve DT visualisation and integration by providing the user with a more immersive form of interaction with the system.

3.3.1. Using Augmented Reality

This section observers the distribution of fields of application, maintenance tasks and the common hardware used[58]. This will highlight the areas relevant to offshore, remote or hazardous locations. This also investigates different AR hardware used with a focus placed on the HMDs as the HoloLens is used in this report. The hardware used is not mutually exclusive however as combining these can increase immersion or control as each has it's own benefits and drawbacks. The application under question defines the system requirements which is ultimately the deciding factor when making decisions about the best practice to follow.

From figure 12 it can be seen that plant maintenance and nuclear industry make up 8% and 21% of fields of application respectively. Mechanical maintenance is another 29% of application that could be related to offshore maintenance[59]. This makes up a total of 58% of possible applications.

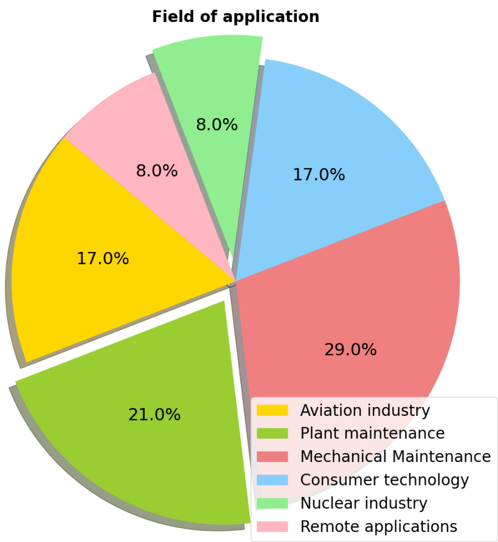

Figure 12: Distribution of Maintenance Tasks[58]

Figure 13 shows the distribution of tasks that AR is used for. Is shows that Inspection and diagnosis takes up 26% of tasks and Training makes up an additional a 15%. Which is 41% of the total uses for AR technology, a significant part of the use cases. Repair, which takes an additional 26%, also be applied to offshore equipment[60] which would account for less that 67% of the tasks.

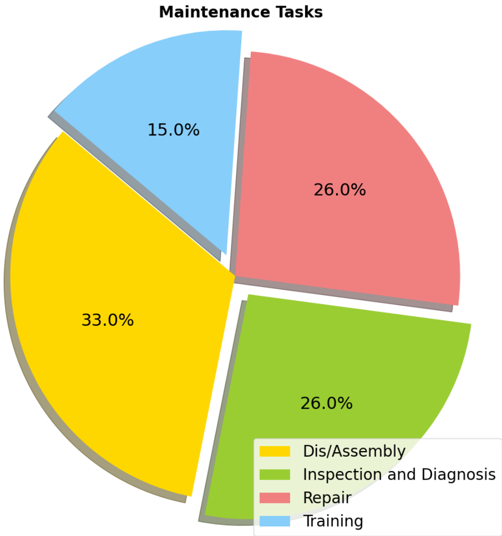

Figure 13: Distribution of Maintenance Tasks[58]

Figure 14 shows the different types of hardware that are used for AR applications. Head mounted displays (HMDs) are the most common, used for 33% of applications. This refers to wearable display such as the HoloLens used in this report but other examples exist. Notably, Apple has recently launched their first "spacial computer" with the Apple Vision Pro[61]. HMDs can also be used to refer to VR headsets of which there are many available on the market today.

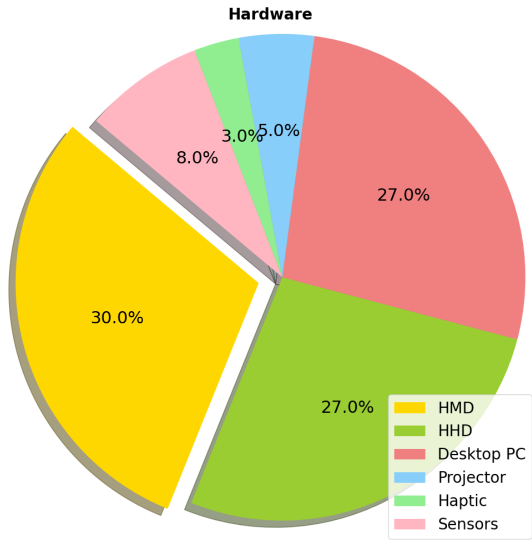

Figure 14: Hardware used in AR maintenance[58]

Desktop PCs are used 27% of the time. They are useful when large processing power is required[62]. They are not portable devices which edge computing could be used to exploit the capabilities of large processing power[63]. This allows the use of lower power devices while keeping the application real-time and low latency.

Next most commonly used hardware joint with desktop PC are Hand Held Displays (HHDs) these are tablets, phones or similar device. This often uses a camera to overlay objects in the screen onto the environment, It utilises the built in Inertial Measurement Unit (IMU) from the HHD to localise itself. These are limited as they require the user to hold a device in front of their face which occupies a hand and is not conducive to seamless integration[64]. They also lack computing power[65].

Projected AR, also refer ed to as projection mapping and or video mapping, uses projected light to augment 3D surfaces[66]. The benefit of projected AR is its capacity to overlay digital content directly onto real-world objects or situations in a way that allows for simultaneous viewing by numerous people without the need for a screen or other equipment. This method only covers only 5% of the hardware but by working towards mobile projection[67] and making it more affordable [68] this could change the way augmented reality in approached.

Sensors are used for 8% of applications, this could be an unexplored area ready for investigation. Especially with the spread of Digital Twins and their inherent requirements for sensors the data could be used to create a more seamless environment with external sensor input[69].

Using a haptics makes up only 3% of the hardware used but can improve the AR and VR experience and immersion[70].By using telehaptics in the VR/AR industry is with multimodal and bilateral interactions they enable human-to-human connections that go beyond the confines of conventional VR/AR engagements by wirelessly delivering and receiving haptic sensations[71, 72]. Despite significant advancements in visual and audio technologies, haptics technology has developed far more slowly. It is more challenging to design a device for the localised sensory input of an ear canal or an eye because skin has tightly packed mechanoreceptors that are scattered over a relatively broad region with complex topography. Furthermore, it is challenging to apply solid state electrical solutions that can treat broad areas without discomfort because to the soft and delicate nature of skin. Soft robotics, a developing field, may provide solutions to this problem [73].

This report focuses on the use of HMDs as they allow the user to operate hands-free to maximise the input the user is able to provide. As is demonstrated, these have become one of the primary methods of deploying AR. This is linked to the fact that microsoft has developed the HoloLens 2 toward industry applications by allying with Trible, creating a hardhat with HoloLens 2 attached[74]. This technology is still lacking in certain areas which need to be addressed for AR applications in maintenance. These include:

- **Hardware Limitations:** They are still uncomfortable to wear and have limited field of view or display resolution. Processing power can also limit the possibilities of the application. Device ergonomics and capabilities need improvement.
- **Tracking Robustness:** AR tracking techniques are not yet robust and reliable enough for harsh industrial environments with occlusions, lighting changes, etc. Improving tracking accuracy and reliability is a key challenge.
- **User-AR Interaction:** More intuitive authoring tools and content management systems are needed to easily create and modify AR content. Determining optimal ways to visualize information and instructions is an open challenge.

Each of these forms of AR have their advantages and disadvantages. They can be combined to create superior engagement and immersion. Concepts combining haptics and HMDs have been made that would provide a fully wearable AR tool[69]. Other applications use HHDs and haptics to immersion[75]. These cases all depend on the desired application.

This section discusses the application of Augmented Reality (AR) in maintenance tasks, focusing on offshore, remote, or hazardous locations. It highlights the distribution of fields of application, maintenance tasks, and common hardware used in AR for maintenance. Plant maintenance, nuclear industry, and mechanical maintenance make up 58% of possible applications. Inspection, diagnosis, and repair account for 41% of AR technology uses. Head-mounted displays (HMDs) are the most common hardware, followed by desktop PCs and handheld displays (HHDs). The report emphasizes the use of HMDs, as they allow hands-free operation and are a primary method of deploying AR. However, challenges such as hardware limitations, tracking robustness, and user-AR interaction need to be addressed for wider adoption of AR in industrial maintenance and other applications. The technology is always maturing and research is ongoing to address these issues.

3.3.2. *Virtual Remote Maintenance and Inspection*

Virtual reality also provides high immersion and presence which can enhance remote inspection. This section will investigate the advantages that VR has on AR and why one would be chosen above the other in different scenarios. It will uncover methods used today and how they can be used for remote Development, training and remote inspections. The drawbacks and limitations are discussed to understand what improvements need to be made to allow their implementation in industry.

The benefits and challenges for each topic are presented in table 2, summarizing the key advantages and potential obstacles associated with the integration of VR and digital twin technologies in Development, Training, and Remote Inspections.

- **Development:** By using VR and Gaze tracking VR can be used to develop AR applications [76]. This is allows for fast iteration enable swift development. As well as development used VR does have it's own merits in comparison to AR. It can be done entirely in a virtual space where aspects of the physical assets can be added into the virtual environment from the DD. Due to the level of immersion however, the DT of the system in question needs to have a reasonable accurate model of the environment such as the facility or a good way of projecting it into the VR space.
- **Training:** VR can create a risk free environment for training by simulating different industries [77]. This enables the capacity to immerse people in a virtual world to train them to handle complex circumstances. Numerous fields

have adopted VR-based training, but for it to be successful, it must be customised to the user's needs, performance, and capabilities[78].

- **Remote inspections:**This also enables a Virtual Remote Maintenance and Inspection (VRMI) uses live 360 degree video streaming from the equipment site, displayed in VR headsets[79]. This allows technicians to virtually inspect the equipment from a remote location.

The overall benefits of VR can be summarised as follows:

- **Immersive Experience:** VR offers a high level of immersion, allowing users to be fully embodied in a simulated environment improving the interface in comparison with other technologies.
- **Risk Reduction:** Especially in training scenarios, VR allows for the simulation of dangerous situations without any real-world risk, ensuring safety while still providing valuable learning experiences.
- **Cost Efficiency:** Over time, VR can reduce costs associated with physical training setups, travel, and equipment, as simulations can replace or augment traditional methods.
- **Accessibility:** VR can transport users to any location or scenario, making previously inaccessible environments readily trainable with the use of drones or underwater vessels.
- **Consistency in Training:** For educational and training purposes, VR ensures that every participant gets a consistent experience, eliminating variables that might exist in real-world training.
- **Enhanced Engagement:** The interactive nature of VR can lead to increased engagement and retention, making it especially useful for educational and marketing purposes.
- **Real-time Collaboration:** Despite geographical distances, individuals can collaborate in a shared virtual space, enhancing teamwork and communication.
- **Rapid Prototyping:** In development and design, VR allows for quick mock-ups of products or environments, enabling faster feedback and iteration.
- **Adaptability:** VR experiences can be tailored to suit the requirements of the application and suit user needs.
- **Data Collection:** VR platforms can collect user data, such as gaze tracking or interaction metrics, providing valuable insights for further refinement and understanding user behavior.

In essence, VR's transformative potential spans across various sectors, from education and training to entertainment and design, offering solutions that are not just innovative but also efficient and user-centric. This does not come without its challenges, however. Integrating VR into inspection workflows may present a steep learning curve for technicians and engineers accustomed to traditional methods. Moreover, there are several technical challenges to overcome to ensure the VR system works seamlessly:

- **Sensor positioning:** Sensors are required to take information about the environment. If this is not accurate does not cover an area this cannot be represented in real time in the

Element	Benefits	Challenges
Development	1. Iterative improvements on interface. 2. Adaptation to market changes and customer needs.	1. Require a good model of the facility. 2. Simulation needs to be accurate
Training	1. Improved job performance. 2. Reduced errors and increased efficiency. 3. Create a standard procedure. 4. No need for expensive equipment.	1. Not hand-on. 2. Need accurate model.
Remote Inspections	1. Reduced travel costs and time. 2. Increased frequency of inspections. 3. Ability to inspect inaccessible locations. 4. Real-time data collection and analysis. 5. Enhanced safety by minimizing human risk.	1. Sensors required for AV. 2. Latency can affect performance. 3. Difficult to ensure validity of data.

Table 2: Benefits and Challenges of Development, Training, and Remote Inspections

Table 3: Comparative analysis of different robotic inspection sensors use in O&M platforms used in industry

Sensor	**Benefit**	**Disadvantage**	**How this could be visualized in AR**
Visual Sensors	Detect defects in structures	Limited in low-light conditions	Overlaying detected defects on the real-world view
Lidar Sensors	Mapping and measuring distances	Can be affected by environmental factors	Displaying 3D models of inspected structures
Ultrasonic Sensors	Detect defects in materials	Limited to certain materials and thicknesses	Visualizing detected defects on the inspected surface
Acoustic Emission Sensors	Monitor structural integrity	Sensitive to environmental noise	Highlighting areas with potential structural issues
Force Sensors	Measure contact force	Limited to contact-based inspections	Displaying force values during contact inspections
Inertial Sensors	Measure motion and orientation	Can be affected by sensor drift	Visualizing motion and orientation data in real-time
RTK GNSS	High-precision positioning	Requires clear line-of-sight to satellites	Displaying precise location information on AR interface
Depth Cloud	Provides 3D spatial information	Can be affected by transparent or reflective surfaces	Representing the environment in 3D space with depth information

VR simulation. As covered in the simulation, modeling and VV&A section the model needs to capture key elements of the PE. Potential solutions could be using multiple cameras or movable cameras like drones or using a symbiotic robot fleet [8] to have a broad cover of the inspection area.

- **Latency:** Since collaborating with a robot in VR includes bilateral communication between the real and virtual environment. If this is done over network connection the bandwidth must be sufficient to transmit sensor data to the virtual environment.

- **Simulation:** Virtual reality relies on the simulation of the environment being adequate. If certain aspects are to be predicted the physics engine or modeling platform must be well tuned to emulate the real world.

The integration of Virtual Reality (VR) into the realms of development, training, and remote inspections presents a transformative approach that holds the potential to redefine traditional methods of O&M. The immersive nature of VR, combined with its ability to simulate intricate real-world scenarios, offers a myriad of advantages ranging from cost savings to enhanced safety protocols. However, as with any emerging technology, the path to seamless integration has some challenges. From ensuring accurate sensor positioning to managing latency and ensuring the fidelity of simulations, there's a need for continuous refinement and innovation. The synergistic potential of combining Digital Twins with Augmented Reality (AR) will be covered in the next section. This combination promises to further enhance the capabilities of remote inspections, offering a more integrated, real-time, and context-aware approach to maintenance and monitoring.

3.4. Reinforcement of Digital Twin

Digital twins already measure a lot of data with various sensors. This section will discuss non-destrucive sensors that can be used in robotic platforms[80]. Table 3 has a list of non-destructive sensors with associated benefits, challenges and method of implementation in augmented reality or virtuality[81]. Provided the platform has a high level of autonomy long range inspection is possible[82].

Sensors are vital in robotic inspection and maintenance platforms, capturing critical data from the environment. In AR, this data can be overlaid onto a user's real-world view to provide contextual insights[83]. For instance, visual sensors can highlight detected defects directly on structures, while Lidar sensors can project 3D models of inspected areas. Ultrasonic sensors[84], adept at detecting material defects, can visualize these defects on the inspected surface. Acoustic emission sensors, which monitor structural integrity, can pinpoint areas with potential issues. Force sensors, used in contact-based inspections, can display real-time force values and provide haptic feedback, and inertial sensors can showcase motion and orientation data. RTK GNSS offers high-precision positioning, visualized directly on the AR interface.

Multi-sensor fusion can be used to combine data from various sensors, offering a comprehensive, enhanced visualization in AR. In essence, sensors bridge the gap between raw data and actionable insights in AR, enhancing the user's understanding and decision-making capabilities.

Services can also be asked of digital twins this could be motion planning or inspection tasks. These factors ca be implemented into the MR platform interface. With a good DT a robot with a high level of autonomy perform in a measured environment[85].

The literature review provides valuable insights into the current state and potential of digital twin, augmented reality, and virtual reality technologies for remote or assisted operations and maintenance. Key findings like the benefits of AR for visualization, VR for immersive training, and digital twins for data-driven monitoring will inform the methodology. This will develop an application that leverages MR interfaces through HMDs to overlay digital twin data on real-world view. This allows for assistance through visualization and created context-awareness for remote maintenance tasks. VR capabilities will be utilized for remote training simulations, reducing risk and costs. The digital twin will integrate multi-sensor data to enable a human-in-the-loop solution to O&M. By building on the synergies identified between digital twins, AR, VR, and autonomous platforms, the methodology aims to demonstrate an integrated approach to remote operations and maintenance enabled by these technologies.

4. Methodology

The methodology first describes the available tools and development platforms for creating a cyber-physical environment by combining the EWK from the jackal robot's sensors and the HoloLens with digital twins of the jackal and facility. It will explore the best process to develop an MR environment capable of improving O&M. This hybrid cyber-physical environment can then be experienced at varying levels of immersion through AR, AV, and VR to suit different use cases. The application enables bi-directional communication between the user wearing the HoloLens and the jackal robot via a networking solution. The jackal robot runs on Robot Operating System (ROS) middleware which facilitates integrating its sensors, control, and communication. The methodology is concluded with a framework developed based on the levels of immersion from the RV continuum.

4.1. Jackal

The Jackal robot [86] is an UGV created by Clearpath Robotics [87] is controlled via Robot Operating System middleware [88]. This operating system is common in robotics research using uses a master server and a publisher subscriber architecture communicating via topics[89]. The base packages provided by Clearpath [90] simple SLAM capabilities, teleoperation using a joystick, keyboard or mouse or by directly setting desired pose.

4.2. Sensors

The sensors provided were the ZED 2 camera [91] and the OUSTER's OS0[92], which can be seen in 4.2.2

4.2.1. ZED 2 Camera

The ZED 2 camera is a stereoscopic camera that can publish the feed of either the left or right camera. Additionally to this basic feature the ZED 2 uses AI in a few different ways. Instead of using photogrammetry, this camera uses neural networks to create point-cloud information. The built in spatial object detection is also very useful for defining the location in space of objects in a scene.

Figure 15: Jackal Robot [86]

4.2.2. 3D Lidar - OUSTER's OS0

This can be used for SLAM[93] applications. Working with a 10% reflectivity at a distance of 35 meters. This requires non reflective surfaces to work best.

Figure 16: ZED 2 Camera(left)[91], laser scan (right)

4.3. HoloLense

Microsoft's HoloLens 2[28], seen in figure17 is targeted at the industry to promote boundless collaboration and increased productivity. This device has a host of capabilities to facilitate this mission such as voice commands, eye tracking, and world-anchoring. It creates a holographic canvas overlayed with the physical environment and there is already an ecosystem of applications that are supported. Tools have been developed by

Figure 17: HoloLens 2

Microsoft to enable developers in making user-centred MR environments. This comes with tutorials, documentation and up to date functionalities for VR and AR development.

4.3.1. Mixed Reality Toolkit (MRTK):

This is a plugin provided by Microsoft that provides a set of features and components used to accelerate MR app development in Unity. This provides support for the HoloLens 2 development[94].

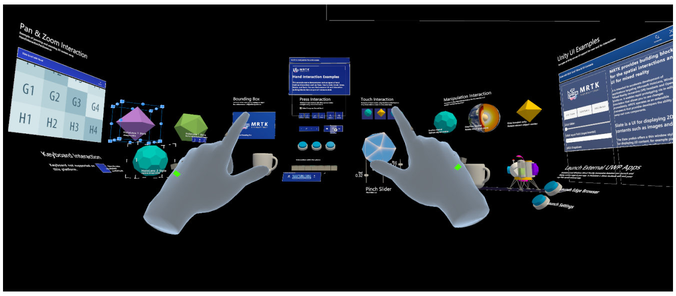

Figure 18: Emulator within unity editor in an example scene

4.4. User Interface

The user interface is designed to be as minimalist to avoid overloading the user which would end up hindering rather than assisting the inspection. The user should be able to decide how much information is required to perform the inspection, so toggles were added that could enable certain features.

4.4.1. Hand Tracking

Using the built in hand-tracking the MRTK package provides a many functionalities that can be useful in creating a minimal yet responsive interface. The hands-up menuis an good example of this. It can be activated by holding the palm up towards the face. The user can then decide to drop their hand , making the interface disappear or they can drag it into the scene, meaning that if the user then drops there hand the menu would remain in it's position. This is useful as it means the scene is initially empty and therefor as minimal as possible and the user can decide to bring up the menu from anywhere they are.

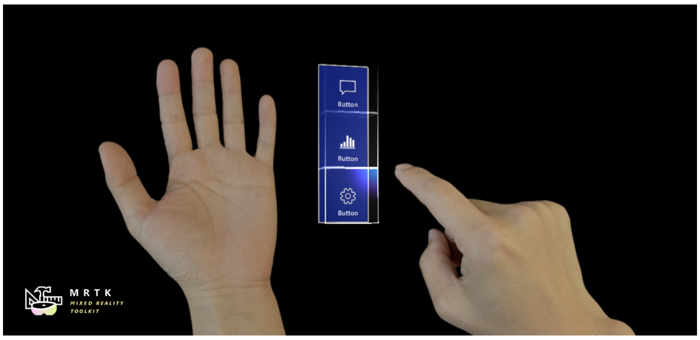

Figure 19: Hands up menu example [94]

4.5. ROS

As previously mentioned ROS was used to operate the Jackal robot. The distribution used was melodic [95], which, although it reached its end of life date in May 2023 was what was installed on the Jackal robot. This meant that a lot of other software choices were made keeping this in mind.

4.5.1. Packages

- **ZED 2 Package[96]:** This provides the SDK to operate the ZED2 camera as well as launch files with corresponding 3D models to open in a simulation.

- **AWS RoboMaker Small Warehouse World[97]:** This is used as the simulated world for the jackal as seen in figure 20. It comes with models of items commonly found in a warehouse.

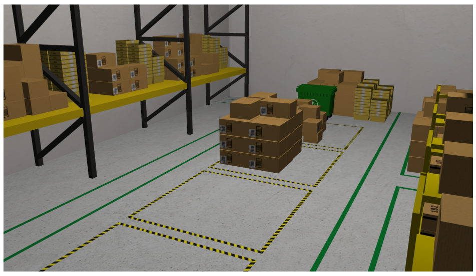

Figure 20: small warehouse in Gazebo

- **ROS-TCP-Endpoint[98]:** This package is used to create an endpoint transmit ROS messages from a Unity scene and vice-versa using the ROS TCP Connector scripts.

- **Jackal packages[99]:**

  - jackal_navigation: This contains the necessary configurations to run the ROS navigation package[100] on the for the Jackal. This is a 2D navigation stack that takes in information from odometry, sensor streams, and a goal pose and outputs safe velocity commands that are sent to a mobile base.
  - jackal_gazebo: This package contains launch files to spawn the Jackal in different example environments.
  - jackal_description: This package provides a URDF model of Jackal. This was useful for adding other sensors to the model. This comes with optional accessories such as a laser that be used for SLAM applications.
  - jackal_control: This contains launch files for the used to control the Jackal such as teleop, localization. The mobility is controlled by the native ROS package diff_drive_controller [101], a controller for differential drive wheel systems. This takes the form of a velocity command, split and sent to 2 wheels. Odometry is computed from the feedback from the hardware, and published.

4.5.2. Differential Drive

As a UGV with four wheels this has the dynamics presented in figure 21.

The body velocity is determined by the x component of the forward velocity vector V and the angular velocity θ of the UGV:

$$v^{\text{body}} = \begin{bmatrix} v_x \\ 0 \\ \dot{\theta} \end{bmatrix}$$

In the world coordinated frame this is:

$$v^{\text{world}} = \begin{bmatrix} v_x \cos\theta \\ v_x \sin\theta \\ \dot{\theta} \end{bmatrix}$$

Twist and linear velocity commands are available to control the Jackal.

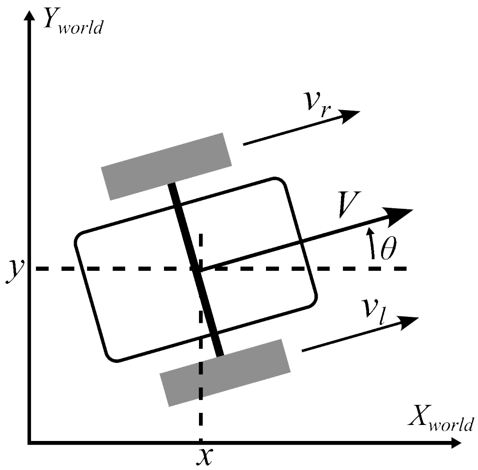

Figure 21: Differential Drive Kinematics [102]

4.6. Development platform

There are a few development platforms freely available. Most notably Unity[103] and Unreal Engine provide a very powerful platforms. Unity was chose for this report as this has good backward development with old versions of linux which will be used due to ROS version being used.

4.7. Scenarios

Using This platform three scenarios will be designed these will serve as demonstrations for

4.7.1. AR Assisted Inspection

Assistance can be brought about in a variety of ways through the use of the DD. This will be broken into 2 categories:

- Visual assistance
  - Mini-map: This can produce a simplified representation of the environment, highlighting only important aspects such as robot and user position and planned trajectory.
  - Camera feed: This is a feed from the stereoscopic camera and can generate a 2D image of the environment from 3 angles which cal then be used to make 3D information.
  - Point cloud: This information is calculated using the depth camera allwing this data to be visualised in the MR environment.
  - Urgent care & Diagnostics: User can be prompted by areas requiring urgent care or can have the option of viewing diagnostics of robots.
- Assisted maneuvers: This takes the form of high level control such as setting a waypoint for the robot to go to. This could be useful if multiple robots were added as this would enable the operator to have a reduced cognitive load for each robot and therefore have the capacity to control a fleet.

4.7.2. AV Remote inspection

Using the EWK and the digital assets, the entire inspection process can be done remotely in a Augmented virtually environment. This could be done over internet although latency is unavoidable and therefore should be taken into account, especially if this were an application with multiple robots [104].

4.7.3. VR Training

Training can be accomplished risk free and relatively cheaply as the entire system could be simulated as a virtual environment. Requiring only the digital assets and understanding of system behaviour. In this case it could be VR or AV. Giving the user an intuition for the real system in a safe environment.

4.8. Immersion Framework

In figure 22 the framework used is presented. This demonstrates how elements go together to build the MR experience. This shows how the System and Jackal DTs provide coherence of the simulation. With ROS packages and Unity physics engine the simulation can be made coherent with a controlled environment. The External sensors on the jackal as well as the ones built into the HMD.

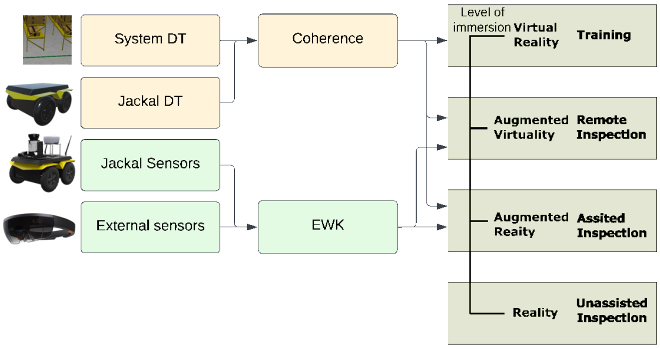

Figure 22: Immersing user into cyber physical space framework

The application needs to be built onto the HoloLens information from the user and the robot should be bi-directional so a networking solution needs to be established. The methodology has outlined the framework that will be used, leveraging the jackal robot's onboard sensors and ROS middleware with ans Unity to create an augmented reality environment optimized for the HoloLens 2. This enabled designing an assisted inspection system with varying levels of immersion from AR to VR. The development platform provided capabilities to import robot models, connect to ROS via plugins, and build a user interface suited for mixed reality. With this groundwork established, the implementation involved experimentally setting up the physical assets including the jackal and its sensors, the HoloLens device, and networking between ROS and Unity to enable real-time communication. The following section details the experimental setup and implementation process to create the cyber-physical MR system proposed.

5. Implementation

The Implementation section details the development process for creating the mixed reality interface using Unity and integrating it with ROS. It begins by describing the setup of the Unity project, including importing the Jackal URDF model and adding ROS communication packages. The robot configuration is then cover in simulation and the real world, followed by an explanation of the ROS networking architecture. Key topics published and subscribed to are listed along with how messages are handled in Unity. The user interface components are then presented - the minimap, camera feed, diagnostics panel, point cloud visualization, and controller. Finally, three scenarios are outlined to demonstrate use cases for augmented reality, virtual reality, and merging simulation with real sensor data. This implementation enables investigating the framework for human-robot collaboration proposed in the methodology.

5.1. Unity Project

Unity [103] was chosen as it is versatile multi-platform engine. This is important as ROS melodic needs to be on a Ubuntu 18.04 system which might not be compatible with some software. There are also packages available for unity that assist in development of HoloLens and ROS applications. Unity editor version 2020.3.48f1 [105] as this has an LTS version that is compatible with Ubuntu 18.04. The following steps were undertaken to set up the Unity project. All code in the project in in C# as this is the native language to Unity. Since ROS 1 is being used all code in the ROS environment is in python 2.

Once created the The following packages were added to the project:

- **URDF Importer[106]:** The Unified Robot Description Format (URDF)[107] is an XML document, representing a robot model. This package allows the importation of a `.urdf` file into unity.
- **ROS-TCP-connection[108]:** This works in conjunction to the ROS package discussed previously. It is built on ROS# [109] which is a set of open source libraries for communicating with ROS from .NET applications such as Unity. The ROS master server IP can then be set in the unity editor to allow unity to send and receive ROS massages. This also has message generation capabilities, which can read `.msg` files and convert them to a C# message class so that the information can be parsed easily.

5.1.1. Importing the URDF

The `.urdf` file is generated from the `.urdf.xacro` file [110] which allows the output urdf to be modified using macros, which makes shorter more readable `.urdf` files. The URDF is then generated using the shell command line:

```
xacro jackal.urdf.xacro > jackal.urdf
```

The URDF importer provides an interface to bring it into the unity project as shown in figure 23.

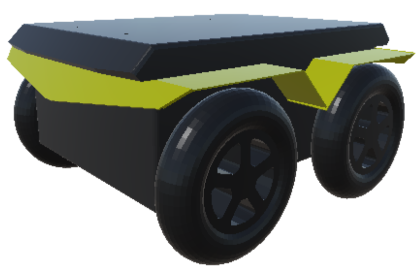

Figure 23: Imported urdf

5.2. *Robot configuration*

The jackal robot URDF is imported into Gazebo with the same ros description package as the unity package in the previous section. with the configuration shown in figure 24.

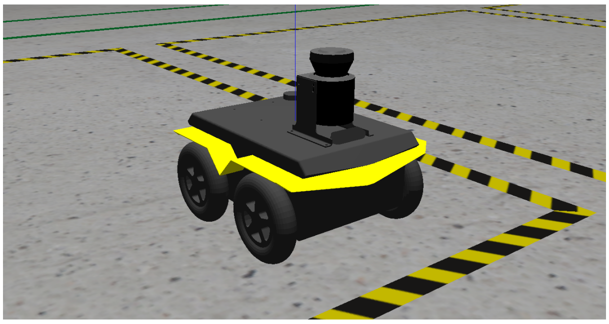

Figure 24: Gazebo configuration for Simulation - DT

The real jackal is equipped as shown in figure 25. The ZED 2 camera is clearly visible. Though, due to unavailability during the duration of this report the LiDAR was not installed on the PE. It was still simulated to demonstrate what could be possible if if had been installed.

Figure 25: Physical configuration

Equipped with these sensors the following topics are generated on the ROS server. This can be thought as the raw or filtered information about the Robot and environment which can then be communicatd via networing.

5.3. *Networking*

The networking is done through ROS with a master server that contains all the information about the sensors. These ”Topics” can sent over network via TCP connection from the ROS-TCP-connection described earlier. This section gives an overview of what information can be accessed by the user as well as what can be communicated from the user to the Unity environment.

5.3.1. *Topics*

The topics in table 4 give a brief description of the information that is available from each topic. These will be

Table 4: ROS Topics and Descriptions

ROS topic	Description
/zed2/color/image_raw	Camera feed from the POV of the Jackal.
/map	Map constructed using ROS's inbuilt SLAM algorithm.
/odom_link	Odometer message that provides the location of the robot in reference to the map.
/tf /move_base/NavfnROS/plan	Trajectory plan of the robot.
/move_base_simple/goal	This is the waypoint target of the jackal.
/cmd_vel	This is the command velocity that is given to the jackal to control it.

These are published to the ROS master in a certain format. For this format to be interpretable by unity these must then be converted using the ”Unity - ROS MessageGeneration” provided by the ROS-TCP-connection package.

5.3.2. *Message generation*

With the Unity package, the following topic message types were generated:

- ImageMsg - Used for camera feed, RBG colour scheme.
- OccupancyGridMsg - Oscupancy grid of map.
- PoseStampedMsg - Pose messege, defining a position and orientation of the robot.
- TfMessageMsg - Tf is a ros tool that contains joint poses of the robot.
- PathMsg - This is a series of points defining a trajectory.
- PointMsg - Defines a 3D vector for position.
- TwistMsg - Command velocity for the Jackal robot.

These are common messages used in ROS networking they are generated into C# so that they can be compiled by Unity. An example generation of the ImageMsg can be found in Appendix C.4.2 with it's ros `.msg` counterpart.

Once this data is compatible with Unity's requirements the networking needs to be completed on the Unity side. By using ROS#, a C# version of ROS similar connections can be made to the ones naive to ROS.

5.3.3. Unity Code

Different classes of subscribers and publishers are made in C# to interpret the data in the environment and communicate with the ROS master. Some examples of snippets of code are provided in this section as pseudo-code but original code can be found on Github.

5.3.4. Subscribers

A subscriber Receives information via ROS networking. In this information is used to be expressed in the mixed reality environment. Below is the pseudo-code made for a subscriber. When the connection is made the subscriber is able to listen for that topic. The `HandleImageMessage` function is then defined to perform a certain action when the message is received.

```
using UnityEngine;
using Unity.Robotics.ROSTCPConnector;
using Unity.Robotics.ROSTCPConnector.
    ROSGeometry;
using RosMessageTypes.Sensor;

public class ExampleSubscriber :
    MonoBehaviour
{
     ROSConnection ros;
     public GameObject Object; //Object to be
      influenced by this message

     public string Topic = "/rostopic/
    topicname"; //Name of topic

     void Start()
     {
         //Get or create the ROSConnection
         ros = ROSConnection.
    GetOrCreateInstance();
         //Subscribe to the topic
         ros.Subscribe<TopicMsg>(imageTopic,
    HandleImageMessage);
     }

     //Define what to do when a message is
    received
     void HandleImageMessage(TopicMsg msg)
     {
         Debug.Log("Message␣received");
     }
}
```

Listing 1: ExampleSubscriber.cs

To capture the information from the sensors and DD so that it can be projected in the Unity MR environment thr following subscribers were made:

- CamSub.cs - Receives the camera feed from the Zed 2 camera and presents it in the user interface.
- MapSub.cs - Used to display map topic generated through a SLAM algorithm in the minimap.
- PntCldSub.cs - Receives 3D Point cloud information and projects it in the Environment. Tjhis can be used to generate a 3D representation of the world in the virtual environment.
- TfSub.cs - Receives the joint position and orientation of the jackal joints.
- TrajSub.cs - Receives the planned trajectory of the jackal. This is genrated as a service provided by in-built ROS package.

The message types and topic names for each of these is presented in Table 5. The camera subscriber can receive the raw image feed from the camera and render it in the mixed reality environment. This allows the user to see the environment from the robot's perspective. The map subscriber receives the occupancy grid of the environment built up by the SLAM algorithm running on the robot. This map can then be rendered to give the user spatial awareness beyond their immediate surroundings. The point cloud subscriber receives the 3D point cloud generated by the depth camera. These points can be projected into the mixed reality environment to visualize the 3D structure of the environment. The TF subscriber receives the transform tree containing the joint positions and orientations of the robot model. This allows the virtual robot to match the configuration of the physical robot. Finally, the trajectory subscriber receives the path plan generated by the navigation stack, which can be rendered as a visualization of the robot's future trajectory.

Script	MesageTypes	Topic Name
CamSub.cs	ImageMsg	/zed2/color/image_raw
MapSub.cs	OccupancyGridMsg	/map
PntCldSub.cs	PoseStampedMsg	/zed2/depth/points
TfSub.cs	TfMessageMsg	/tf
TrajSub.cs	PathMsg	/move_base/Nav/plan

Table 5: Subscriber scripts

5.3.5. *Publishers*

Publishers are used to send information to the ROS master. This can be used to activate certain services of control the Jackal directly. The C# pseudo-code Structure for a publisher is presented bellow. The ROS connection is made and, using the topic name this is transmitted to the ROS master.

```
using UnityEngine;
using Unity.Robotics.ROSTCPConnector;
using RosMessageTypes.Geometry;
using RosMessageTypes.Std;
using System.Collections;

public class ExamplePublisher :
    MonoBehaviour
{
    ROSConnection ros;
    public string topicName = "/rostopic/
    topicname"; //Name of topic
    public GameObject Object; //Object that
    influences the message

    void Start()
    {
        // Start the ROS connection
        ros = ROSConnection.
    GetOrCreateInstance();

         //Register the publisher
        ros.RegisterPublisher<PoseStampedMsg
    >(topicName);

        // Start coroutine to publish
    waypoint once a second
        StartCoroutine(PublishMessage());
    }

    IEnumerator PublishMessage()
    {
        // Check that the ROS node is
    connected to avoid errors
        while (true)
        {
            // Create a new message
            TopicMsg MessageMsg = new
    TopicMsg();

            // Publish the position and
    rotation of the waypoint
            ros.Publish(topicName,
    MessageMsg);

        }
    }
}
```

Listing 2: ExamplePublisher.cs

To send commands to the Jackal. The following publishers were created:

- WaypointPub.cs - sends the desired waypoint for the jackal robot.
- JoystickPub.cs - Sends velocity commands based on the orientation of the hand.

Table 6 show the publishers and their associated message type alongside the ROS topic name. The waypoint publisher allows the user to control the Jackal via waypoint designation on the mini-map. This is a service that can be accomplished by the PE directly or simulated via VE of the DT. The Joystick publisher allows the user to control the robot with joysticks. This is sends velocity and andular velocity commands to Jackal.

Script	MesageTypes	Topic Name
WaypointPub.cs	PointMsg	/move_base_simple/goal
JoystickPub.cs	TwistMsg	/cmd_vel

Table 6: Publisher Scripts

With theses publishers and subscribers able to communicate information other calsses are required to complete the environment. These demonstrate the possible methods for development as well as explains some of the object interactions in the user interface. They are as follows:

- DebugLogger.cs - This was used for development but is also useful to an operator as it provides information about events and interactions that occur in the virtual environment.
- ObjectToggle.cs - This is connected to the relevant toggle switch in the menu so that objects can be toggled on and off to suit the users requirements.
- ResetPosition.cs - This resets certain compenent to tehir original loaction. This avoids the virtual environment becoming messy.
- SliderMagnet.cs - This pulls the the controller sliders to 0 they are not being interacted with. This means the robot will stop moving if the HoloLens looses track of the hands.
- carController.cs - This is used to control the Digital twin using unities wheel collider, taking advantage of the built in physics engine.

These additional classes make the development easier with the DebugLogger, the environment is kept organised with the ObjectToggle the ResetPosition. Safety precautions are taken care of for scenarios where hand tracking is lost with the SliderMagnet. The final utility is the carController, which utilises the physics engine to simulate the movement of a UGV.

With the combination of subscribers, publisher and utility classes the environment can be achieved. A User Interface (UI) is created in accordance with requirements in the literature review. Different scenarios are then designed to investigate the framework established in the methedology. The projects is then built from the unity project using the appropriate settings for the HoloLens 2.

5.4. User interface

This section describes the user interface designed. It has the objective of being minimalist yet flexible depending on the user requirements. This will first cover how the UI is presented in Unity and in the real world environment. The elements that make up the User interface willl then be covered.

The user interface is shown in figure 26, captured by the orthogonal view in Unity. This is comprised of a camera feed, mini-map, controller and control panel to toggle functionalities and adjust setting.

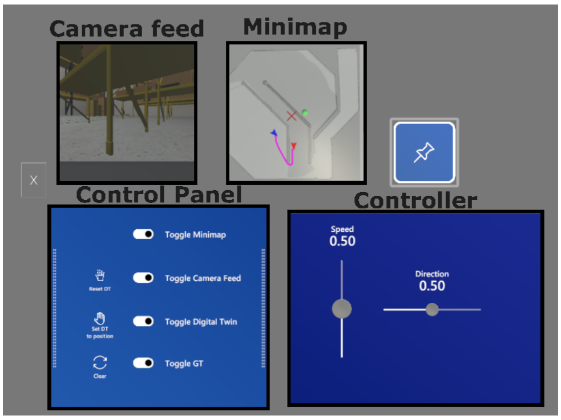

Figure 26: User Interface

This UI can be opened by using the palm up detection covered in the methodology. This can be dragged into the world so that the operator can go back to being hands free. This is demonstrated in figure 27.

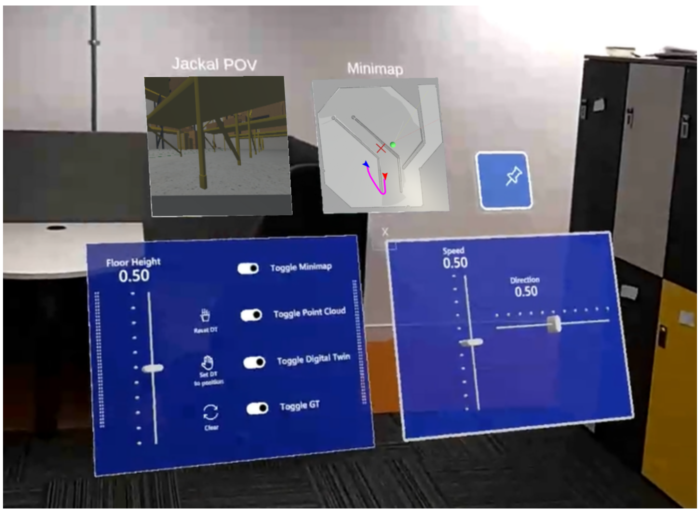

Figure 27: User interface in the world environment

The separate sub components of this UI can each be explored further to explore additional functionalities.

5.4.1. Mini-map

The a mini-map is a tool that can give a simplified representation of the environment. This can show only relevant information to the inspection, highlighting areas of interest or priority. The user can also interact with it directly to input commands such as setting way points for the robot.

The mini-map displays the position of the digital twin, the physical jackal as well as the player and origin as shown in figure 28:

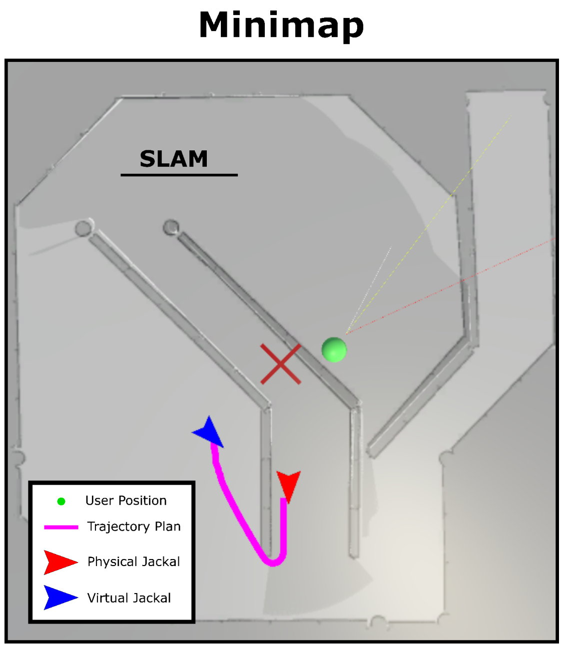

Figure 28: Mini-map

5.4.2. Camera

The camera feed enables the user to see from the robots point of vue which could grant access areas out of human reach.

The camera feed in figure 29 provides a point of view from the Jackals perspective. This shows the simulated camera feed. This is projected to a plane in the virtual space, where the user can toggle it using the control panel.

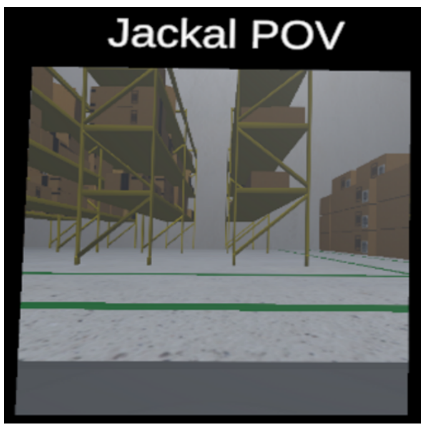

Figure 29: Camera Feed

5.4.3. Diagnostics

The diagnostics tool shown in figure 30 is provided by the MRTK. This is useful in gauging the bandwidth used. It also visualises the frames skipped with the green and red line displayed.

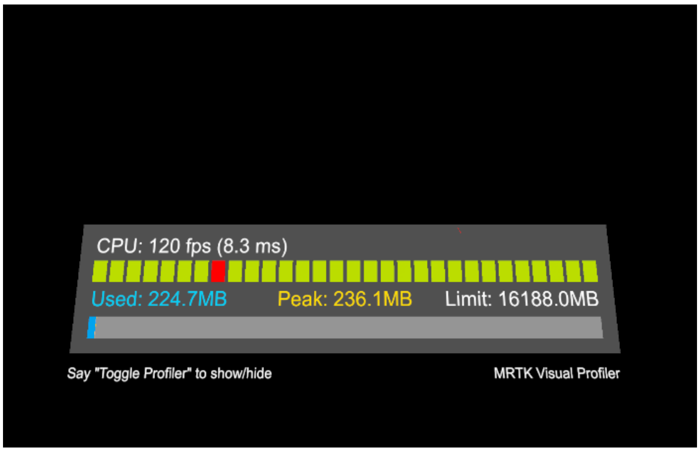

Figure 30: Diagnostics Tool

This information is useful in gauging processing requirements of certain functions such as the point cloud data.

5.4.4. Point clouds

With the point clouds generated by the ZED 2 camera the environment can be modeled in real-time. Overlaying the environment onto itself might be more distracting and a waste of processing power but in the case of VR or AV this could prove beneficial.

Figure 31 shows the point cloud in the environment. Note the red line in the diagnostics viewer, signifying the skipped frames. Displaying point cloud information requires a lot of processing power slowing down the UI.

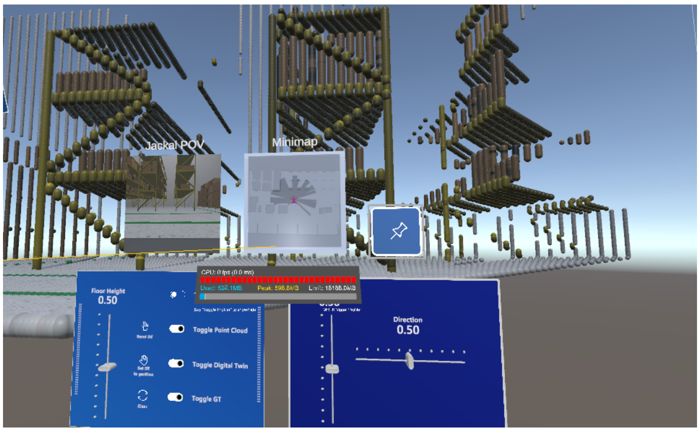

Figure 31: Point Cloud Data

These visualisation are useful for VR Training giving the user an understanding of the robots perspective, gaining insight into how the system works. AV Remote inspection the real world could be overlaid on to the digital asset. The next step in this application is to create a user input in the form of a controller.

5.4.5. Controller

A simple controller was designed. The goal of this is to provide a simple mode of tele-operating the jackal robot. The command velocity and angular velocity are modified using the control sliders.

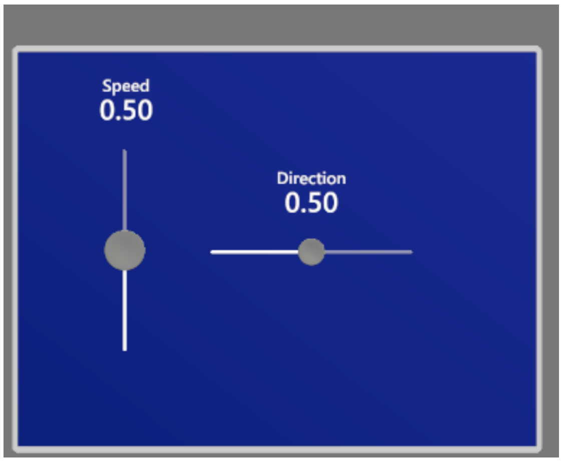

Figure 32: Controller

5.5. Environments

The Jackal can be simulated in an environment as shown in figure 33 with the AR representation projected in the unity environment.

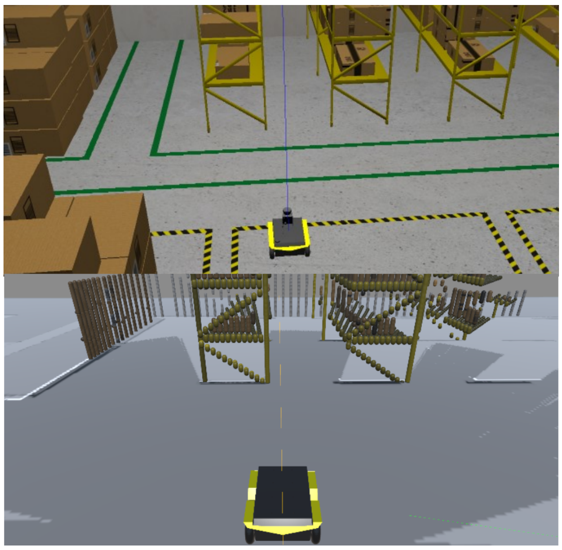

Figure 33: Simulated, Gazebo (top) and Unity Virtual(bottom) Environments

With these elements of of the user interface and the Virtual representation of the data, scenarios can be defined based on the methodology framework and literature review.

The 3 levels of Immersion of AR, AV and VR all serve there own purpose. This will describe how the information acquired from the physical and digital assets can be used in each of these environments

Table 7: Heuristic Evaluation Criteria

Heuristic	Description
Learn-ability	How easy is it for users to accomplish basic tasks the first time they encounter the design, reflected by time taken for a new user to complete the scenario and number of user errors made during the first attempt.
Efficiency	Speed at which users can perform tasks once they have learned the design. Reflected by time taken to complete the scenario in subsequent attempts and reduction in errors with repeated tasks.
Errors	Number of errors users make, severity of errors, and how easily they can be recovered.
Satisfaction	Ease of use and comfort of the design, reflected by user feedback or ratings post scenario, qualitative feedback on specific elements or stages in the scenario.
Cognitive Load	Mental strain cause by interface on the user, determined by users' subjective ratings on difficulty or complexity as well as number of pauses or breaks taken by a user during a task.
Flexibility and Efficiency of Use	Presence of shortcuts for expert users. Whether the interface caters to both novice and expert users. Measured by the availability and use of advanced features, and user feedback on the range and depth of the interface.
Consistency and Standards	Whether interface elements and actions are consistent across the scenarios. Identification of varying commands or feedback for similar tasks across scenarios.
Feedback	System feedback on user actions. Clarity and timeliness of feedback. Detected through identification of inconsistent commands or feedback for alike tasks in different scenarios.
Visibility of System Status	Information provided about system state. Based on the regularity of system updates and user-reported clarity and comprehension of the system status.

5.6. Task Design

To demonstrate the capabilities of this application 3 scenarios were designed. Due to component availability, the tasks were designed around the use of the HoloLens. With minor changes in the configuration these application could be loaded onto a VR headset to allow for a fully virtual environment. Table 7 defines the heuristics upon which the criteria will be judged.

Scenario 1: Manage the jackal in a simulated environment.

Objective: Familiarize the user with the Jackal's control interface and system response.

The user is placed in a virtual space where a simulated version of the Jackal is rendered. Here, the participant has the opportunity to learn the intricacies of operating the Jackal, navigating through virtual terrains and obstacles. The benefits of such a scenario are two-fold: it negates any risks related to damage or errors in the real world, and it ensures that when the user moves to more complex scenarios, they are well-versed in basic Jackal operations.

Scenario 2: Perform an remote inspection.

Objective: Use the Jackal's sensor data to gather insights from a remote facility.

The user is embedded in a digital twin of a particular facility. As the Jackal navigates the real facility, data from its suite of sensors is streamed in real-time and overlaid onto the digital representation. This creates a merged reality for the user, intertwining actual sensor data with the digital facility. The virtual representation offers context, ensuring the user isn't just interpreting raw sensor data but is also aware of its relevance to the digital space.

Scenario 3: Perform an assisted inspection.

Objective: Showcase the benefits of HITL using augmented reality during on-site inspections.

In this scenario, the user shares a physical space with the Jackal robot. While the user might be able to see the facility with their own eyes, the HoloLens overlays additional information provided by the Jackal's sensors. A crucial element in this scenario is the Jackal's LiDAR system, which continually scans the environment. The resultant mapping data can be visualized through the HoloLens, offering an augmented perspective that highlights potential areas of interest or concern in the facility. The real-time AR interface assists the user in making more informed decisions about the facility's status and any necessary interventions.

Four Participant were first briefed on how to use the HoloLens 2 and given 10 minutes to get accustomed to its use. They were then given 3 attempts at each of these scenarios. To allow them to get used to the controls. They were then asked to rank: Navigation, Minimap, User Interface and sensor visualisation using the heuristics from table 7.

Table 8: Compilation of heuristic points for each participant

Heuristics	Minimap		Visualisation		User Interface		Navigation		Total	
	+	-	+	-	+	-	+	-	+	-
Learnability	2		3		3			3	8	3
Efficiency	3			2	1	2	1	3	5	7
Errors	2	1			1	4		3	3	8
Satisfaction	1		2	2	1	3		4	4	9
Cognitive Load	2			2		1		3	2	6
Flexibility and Efficiency of Use			3	1	1	1	1	3	5	5
Consistency and Standards	1			2				2	1	4
Feedback	1	2	2	1			1	2	4	5
Visibility of System Status	1		1	3	1	4	1	3	4	10
Total	15	2	12	13	6	13	8	20	41	52

6. Results & Analysis

The study aimed to assess the usability of the Jackal's control interface and system response across three different scenarios using the HoloLens 2. The participants, familiarized with the HoloLens 2, were exposed to these scenarios and were then asked to evaluate various elements like Navigation, Minimap, User Interface, and Sensor Visualisation using the heuristic criteria outlined in the implementation.

From the collected data presented in table 8, each heuristic was rigorously evaluated by considering both positive and negative feedback from each participant. The score is calculated as the difference between the positive and negative value. Considering that every category (such as Navigation, Minimap, etc.) could receive a maximum total score of ±36 and each individual heuristic could receive a score up to ±16, the total possible range for the final score was ±144.

The summarized results from the heuristic evaluation indicate a greater tilt towards the negative, with a total of 41 positive feedback points and 52 negative feedback points, giving final score of 11. Among the evaluated categories, the Minimap received the highest positive score of 13. This is indicative of its clarity and effectiveness in tracking both the robot and the user's location and trajectory, ensuring fewer negative evaluations. Following this, sensor visualisation secured an overall score of -1. The simplicity of the User Interface was lauded, especially in scenarios where users had to comprehend and act upon data quickly.

Visualisation, serving as a critical element in the scenarios, especially in the "remote inspection" scenario where sensor data is superimposed on a digital twin, revealed mixed responses, shedding light on areas of improvement.

Navigation also played an instrumental role in the simulated environment where participants navigated the Jackal, indicating the importance of intuitive and efficient navigation controls for a seamless user experience

6.1. Challenges

6.1.1. Processing power

Since the entire unity environment is built onto the HoloLens the processing power is limited to a Snapdragon 850 processor, introduced in 2018. Although this was generaly adequate, it proved to have some lag when point clouds were introduced even after reducing the amount of point significantly.

6.1.2. Hand Tracking

Although the software is able to recognise the shape, position and orientation of the hands very well it is not able to track the hands when they are not in the feild of view of the user. This means that to control the jackal using only holoLens would require the user to keep their hands in the frame at all times. To make this more robust a few methods could be used:

- **External cameras:** This would mean the handtracking does not only rely on the HoloLens cameras allowing the user to look away from their hands. This would still require the hands to be visible which limit how robust this solution can be.

- **Tracking Gloves:** Gloves with sensors built in would remove all necessity for visually tracking the hands. This is most likely as the most robust form of hand tracking.

- **Physical Controller:** This could include any other for of controller such as a rmote control, screen or keyboard. This could work in conjunction with the HoloLens where th latter would only serve as a visulaisation and prompting tool for the user. This is most likely the best solution currrently as there are already robust physical controller on the market that could be combined with the HoloLens.

6.1.3. Networking

Once the app is built onto the HoloLens there is no way of changing the IP address that it connects to. When configuring the networking for the, the IP's change which means the app needs to be rebuilt for the networking to take place. This could be solved by setting up a static IP address. In ROS 2 however networking is made significantly easier. There is no ROS master and IP addresses are nor required for successful networking. As long as nodes are on the same network they will find each other.

6.1.4. Compatablility issues

Since the jackal used for testing was shared amongst a large group of researchers modifying its operating system was restricted as much as possible. The version of Linux currently installed reached its end of life in may 2023, which although recent, many of the dependencies for this project have versions no longer compatible with this. Many of these newer versions provide tools that would aid in development. These include the newer ZED2 packages that use AI for object detection and recognition. To facilitate developing state of the art technology it would be strongly recommended to upgrade this operating system.

6.2. Comparison with State of the art

The application described allows for remote inspection using a Jackal robot and VR/AR visualization through the HoloLens 2. It streams real-time sensor data from the Jackal into a digital twin representation seen through the HoloLens. This creates a merged reality for remote monitoring. It also enables assisted inspection by overlaying sensor data on the real environment.

Some key advantages of this application over other state of the art solutions:

- Provides both remote and assisted inspection capabilities in one system. Many other solutions focus on only one.
- Uses an unmanned ground vehicle (Jackal) for mobility and data collection. This is less common than drones or stationary setups.
- Leverages AR through HoloLens 2 for on-site assistance. More advanced than solutions relying only on smartphones or tablets.
- Allows user familiarization through simulated environments. This trains inspectors prior to real-world deployment.

Some limitations compared to other state of the art:

- Reliance on HoloLens 2 could limit widespread adoption due to cost. Other solutions utilize cheaper AR devices.
- Hand tracking capabilities are basic compared to solutions incorporating depth cameras or gloves.
- Networking and compatibility issues may hinder development of more advanced features.

Overall, the application provides a unique combination of remote and assisted inspection. But costs and technical limitations prevent it from surpassing all state of the art solutions currently. Targeted improvements could make it more competitive.

7. Discussion

The proposed system combining digital twins and the level of immersion defined by augmented reality, and virtual reality or augmented virtuality, shows promise for transforming inspection and maintenance procedures in remote, hazardous, or complex environments. The ability to immerse operators in a rich cyber-physical environment can enhance their perception, understanding, and control compared to traditional approaches. While the implemented prototype demonstrated initial feasibility, further research and development could help realize the full potential of this approach.

A key benefit of the system is enabling remote operation, reducing or eliminating the need for on-site human presence. This improves safety by keeping operators out of dangerous environments. It also reduces operational costs by minimizing travel and on-site staffing requirements. However, some tasks may still require physical intervention, limiting full remote capability. Advances in robot autonomy could help address this. The addition of unmanned aerial or ground vehicles could provide movable sensor platforms and proxies for physical intervention.

VR also allows training scenarios to be simulated digitally. This is safer, cheaper, and more readily accessible than real-world facilities. Scenarios impossible to recreate physically can be simulated, expanding training possibilities. The VR environment can also be used for collaborative inspection, with multiple remote experts immersed to share perspectives.

While the implemented prototype relied on the HoloLens for AR capabilities, other devices may offer more flexible or cost-effective solutions. Smartphones and tablets, while less immersive, provide mobility and accessibility. As AR headsets mature, they could rival the HoloLens' capabilities at lower costs. The range of interface options should be explored to balance affordability, immersion, and mobility based on application needs.

There are also open research questions around optimizing multi-modal data fusion and environment representations. Effectively fusing and presenting data from diverse sensors poses perception and cognition challenges. Determining optimal modalities of presenting digital twin data in AR/VR also warrants investigation. With bandwidth limitations, transmitting raw sensor streams may not be practical, necessitating intermediary processing to extract salient information. This could be aided by edge computing resources. There is opportunity for intelligent filtering, fusion, and reconstruction techniques to create rich remote inspection experiences.

While the prototype implemented basic capabilities, significant work remains to develop robust real-world systems. Technical challenges around, autonomy, networking, interface design, and digital twin fidelity must be overcome. Overall, the fusion of digital twin, AR, and VR technologies is compelling but still emerging. Considerable multidisciplinary research combining robotics, sensing, human factors, visualization, and simulation will be essential to maturing these systems for practical deployment. This project provided promising initial evidence but extensive future work is needed to fully validate the concepts.

8. Conclusion

The proposed system is a novel approach to inspection that combines the benefits of digital twins, AR, and VR. The system has the potential to improved the way inspections are performed, making them safer, more efficient, and more cost-effective.

The key achievements of the project include:

- The development of a novel framework used to define O&M scenarios.
- Development of three scenarios in VR, AV and VR.
- User study demonstration the benefits and challenges in the solution.

The primary benefits of the system include:

- Increased safety: The system can reduce the risk of injury to human inspectors.
- Increased efficiency: The system can reduce the time and cost of inspections by assisting in the inspection and elevating cognitive load from the operator.
- Collaboration potential: With a virtual environment physical location is not imprtant so many users can collaborate from different locations.

In conclusion, this project demonstrated the potential of MR and DT technologies to transform maintenance and inspection procedures in challenging, inaccessible environments. A proof-of-concept system was implemented using a robot platform with sensor data streamed to a HoloLens device. This allowed remote operation, assisted on-site inspection, and virtual training scenarios leveraging both real-time and simulated data.

The prototype illustrated the capabilities of immersive cyber-physical visualization and control through the fusion of real and digital environments. It enhances perception, understanding, and human oversight compared to conventional approaches. While promising, there are substantial technical hurdles to realize robust and reliable implementations of such systems. Ongoing research across disciplines including robotics, sensing, human-computer interaction, and visualization will be critical to address these challenges.

Although development made easier with a growing number of resources available, This project revealed the challenges in implementing AR technologies with inspection and maintenance. Substantial future work is required to improve the DT and the representation in the virtual environment. However, the potential benefits of safety, reduced cost, and improved efficiency provide compelling motivation.

In summary, augmented reality, virtual reality, and digital twin technologies could play a transformational role in inspection and maintenance procedures for remote, hazardous, or complex infrastructure. The results confirm the underlying value proposition, while also highlighting areas needing improvement. Robust real-world implementations would require improved hardware software. While future progress is needed, this project contributed evidence that these technologies could fundamentally advance industrial inspection and maintenance capabilities.

9. Future Work

Based on the results of the project, there are a number of potential areas for future work:

- **Improving DT:** The development of a more sophisticated digital twin that can better capture the physical properties of the asset being inspected. More advanced physics modeling and higher fidelity environments could improve understanding of asset behavior and detect-ability of anomalies.
- **Improving AR:** The development of a more immersive AR experience that can provide inspectors with a more realistic view of the asset being inspected. Photo-realistic rendering, expanded sensory modalities, and improved ergonomics could enhance the operator's perception of the remote environment.
- **More in depth Training:** The development of a more robust VR training environment that can be used to train inspectors on how to inspect different types of assets. Large libraries of detailed digital asset models would enable comprehensive training for diverse inspection tasks.
- **Adapting framework:** The adaptation of the system to other applications or environments, such as the inspection of buildings or the inspection of pipelines. The system architecture could be generalized to work with different robot platforms, sensors, and digital twins tailored to other domains.
- **Improving autonomy:** Integration of more autonomous capabilities to enable the robot to carry out inspection tasks semi-autonomously, reducing operator burden. Advanced computer vision and anomaly detection algorithms could be incorporated. Addition of unmanned aerial vehicles to provide aerial vantage points and access for inspection scenarios where ground robots have limitations.
- **Improved networking:** Compute capabilities, and edge computing solutions to enable low latency data transfer and processing for seamless AR/VR experiences.
- **Conduct Quantitative study:** Conducting user studies to quantitatively validate the effectiveness of the system for training, inspection, and remote collaboration. Both performance metrics and subjective assessments should be gathered.

There are extensive opportunities to build on the foundations demonstrated in this project to realize next generation inspection and maintenance solutions. Pursuing these research directions could help overcome limitations of current paradigms.

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10. Appendix

Appendix A. Development environment

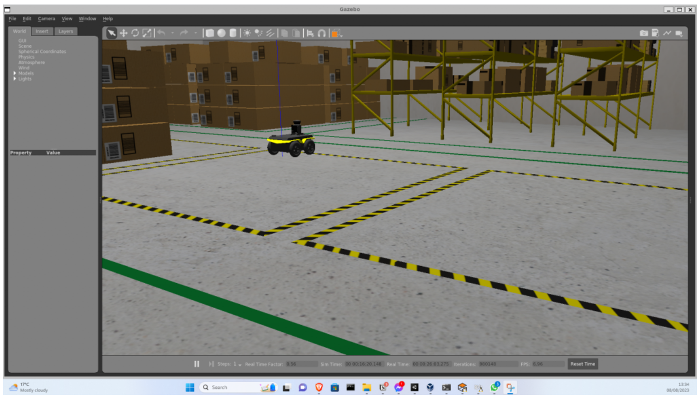

Figure A.34: Gazebo simulation of small warehouse world

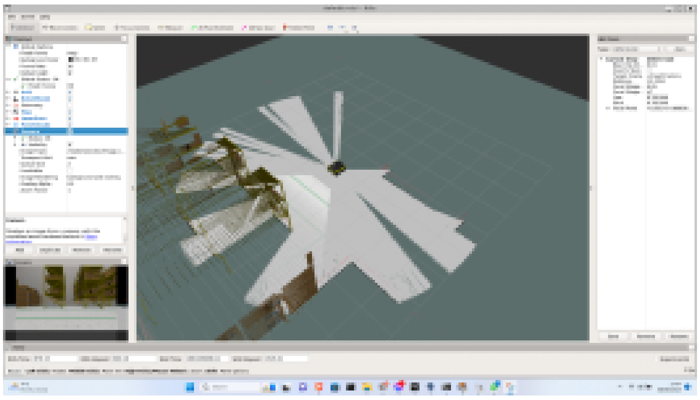

Figure A.35: RVIZ visualization

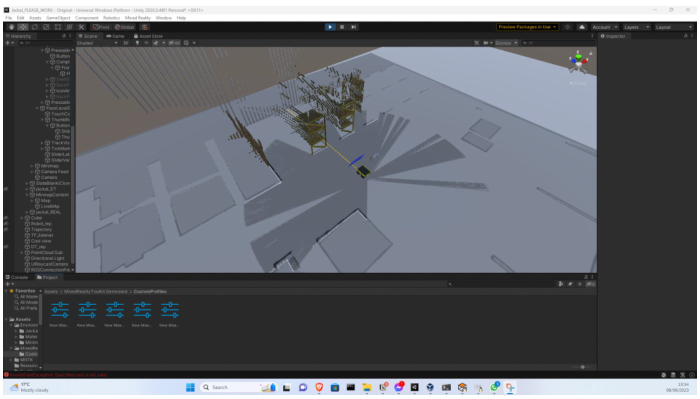

Figure A.36: Unity development environment

Appendix B. Map of the inspection environment

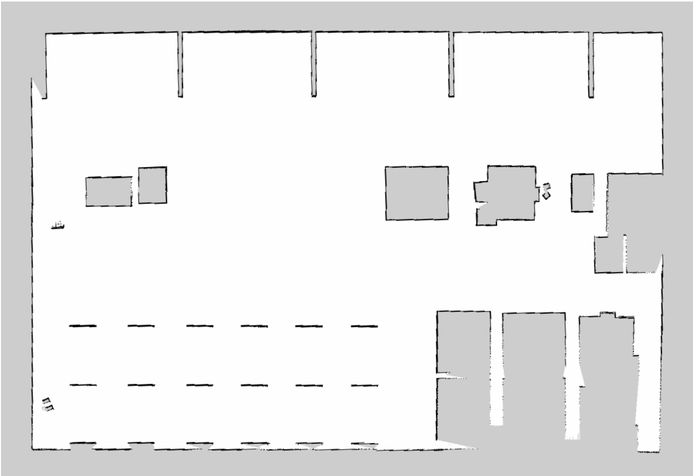

Figure B.37: Map of small warehouse world

Appendix C. word search

Appendix C.1. Top phrases per topic

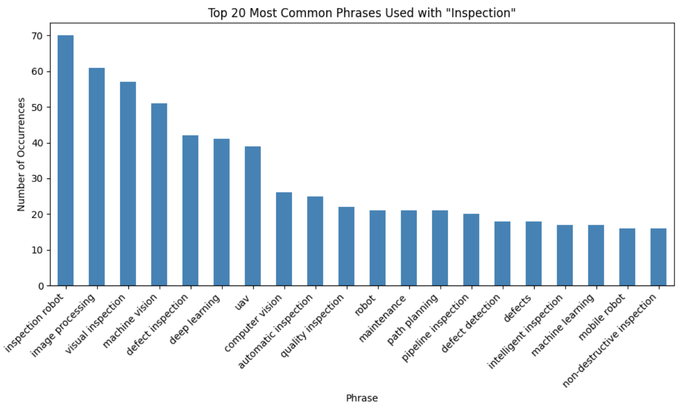

Figure C.38: Top phrases associated with the topic ”Inspection”

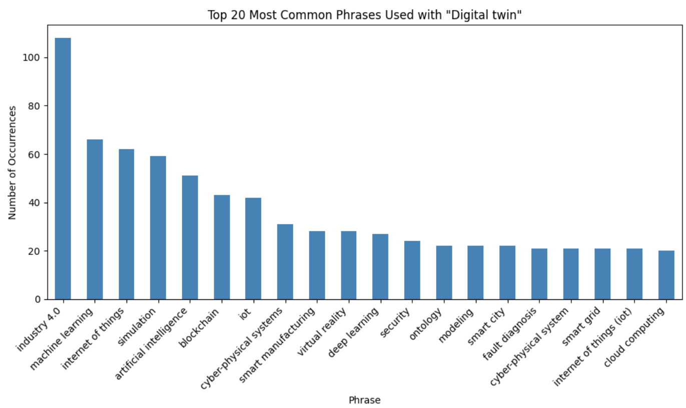

Figure C.39: Top phrases associated with the topic ”Digital Twin”

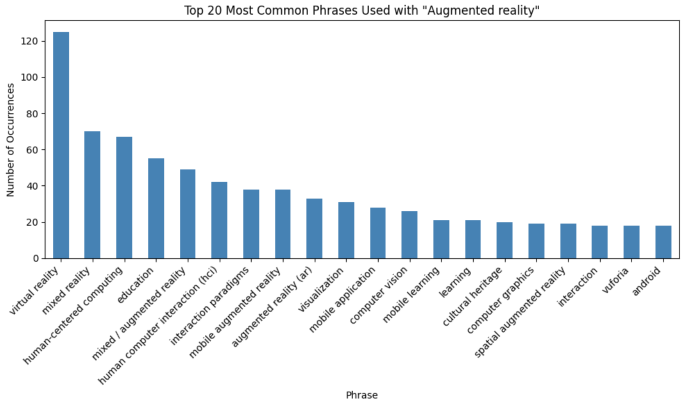

Figure C.40: Top phrases associated with the topic ”Augmented Reality”

Appendix C.2. Top common phrases per topic

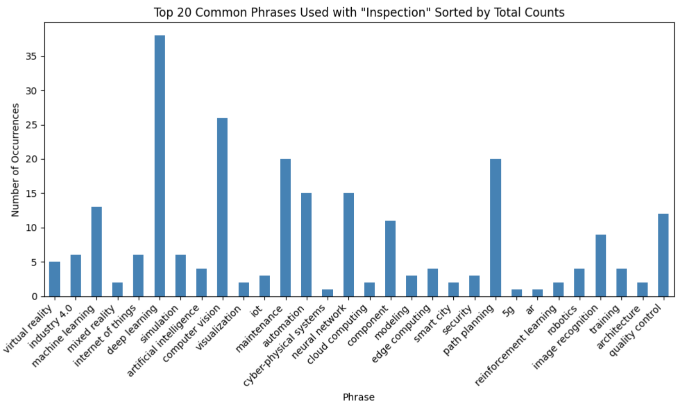

Figure C.41: Most common phrases used in the ”Inspection” topic

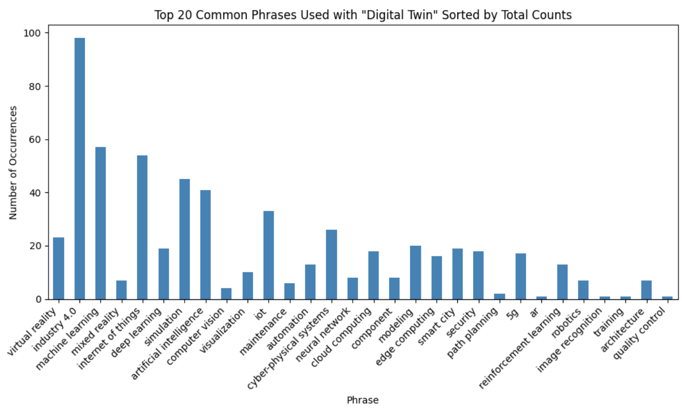

Figure C.42: Most common phrases used in the ”Digital Twin” topic

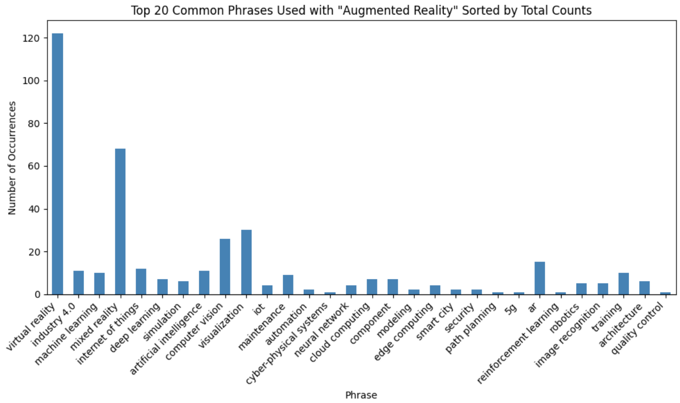

Figure C.43: Most common phrases used in the "Augmented Reality" topic

Appendix C.3. Word-clouds

Appendix C.3.1. Word-cloud of common words

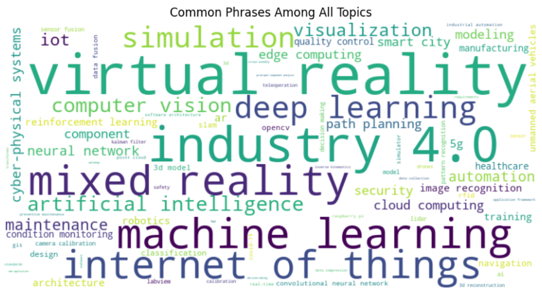

Figure C.44: Phrases commonly used in all categories

Appendix C.3.2. Word-clouds by category

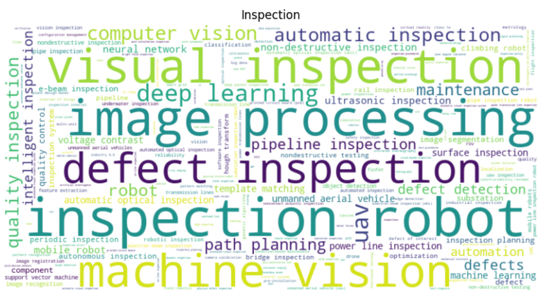

Figure C.45: Phrases commonly used in the "Inspection" topic

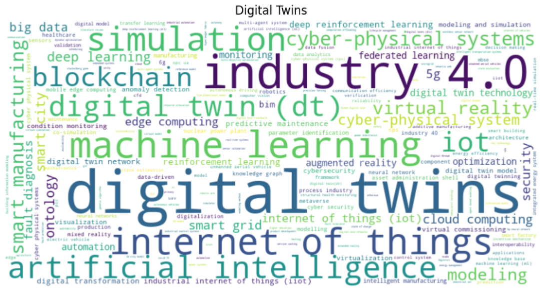

Figure C.46: Phrases commonly used in the "Digital Twin" topic

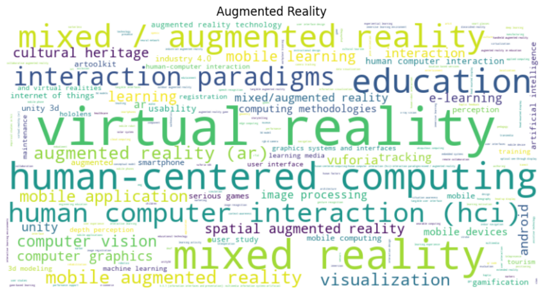

Figure C.47: Phrases commonly used in the "Augmented Reality" topic

Appendix C.4. C# Code

For full code visit: https://github.com/oscell/MSc_HoloLens_Jackal_2391076/tree/main/Reportfiles/CSharp

Appendix C.4.1. Subscribers example

```
using UnityEngine;
using Unity.Robotics.ROSTCPConnector;
using Unity.Robotics.ROSTCPConnector.ROSGeometry;
using RosMessageTypes.Sensor;
using System;

public class CameraSubscriber : MonoBehaviour
{
    ROSConnection ros;
    public Material imageMaterial;

    public string imageTopic = "/realsense/color/image_raw";
    public float maxFrameRate = 10f; // Process images at a maximum of 10 FPS.

    Texture2D texture;

    private float lastUpdateTime;

    void Start()
    {
        Debug.Log("Image subscriber started");
        ros = ROSConnection.GetOrCreateInstance();

        ros.Subscribe<ImageMsg>(imageTopic, HandleImageMessage);

        texture = new Texture2D(640, 480, TextureFormat.RGB24, false);
    }

void HandleImageMessage(ImageMsg msg)
{
    // Check if enough time has passed since the last update
    float currentTime = Time.time;
    if (currentTime - lastUpdateTime < 1f / maxFrameRate)
    {
        return; // Not enough time has passed, skip this frame.
    }
    lastUpdateTime = currentTime;

    // Convert BGR to RGB
    byte[] rgbData = new byte[msg.data.Length];
    for (int i = 0; i < msg.data.Length / 3; i++)
    {
        rgbData[i * 3 + 0] = msg.data[i * 3 + 2];
        rgbData[i * 3 + 1] = msg.data[i * 3 + 1];
        rgbData[i * 3 + 2] = msg.data[i * 3 + 0];
    }

    // Use LoadRawTextureData to update the texture
    texture.LoadRawTextureData(rgbData);
    texture.Apply();

    // Assign the texture to the material
    if (imageMaterial != null)
    {
        imageMaterial.mainTexture = texture;
    }
    else
    {
        Debug.LogError("No material provided to apply the texture to.");
    }
}



}
```

Listing 3: CameraSubscriber.cs

Appendix C.4.2. Publisher example

```
using UnityEngine;
using RosSharp.RosBridgeClient;
using RosSharp.RosBridgeClient.MessageTypes.
    Geometry;

public class JoystickPublisher :
    MonoBehaviour
{
     private RosSocket rosSocket;
     public string topicName = "/cmd_vel";

     // Assuming these are the axes for your
    joystick
     public string linearAxis = "Vertical";
     public string angularAxis = "Horizontal"
    ;

     // Rate at which to send messages (in Hz
    )
     public float publishRate = 10.0f;

     private float timeElapsed;

     void Start()
     {
          // Establish a connection to a
    rosbridge server
          rosSocket = new RosSocket(new
    RosSharp.RosBridgeClient.Protocols.
    WebSocketNetProtocol("ws://localhost
    :9090"));

          timeElapsed = 0;
     }

     void Update()
     {
          timeElapsed += Time.deltaTime;

          // If enough time has passed...
          if (timeElapsed > 1.0f / publishRate
    )
          {
               // Reset the timer
               timeElapsed -= 1.0f /
    publishRate;

               // Read joystick input
               Vector3 linearVel = new Vector3(
    Input.GetAxis(linearAxis), 0, 0);
               Vector3 angularVel = new Vector3
    (0, 0, -Input.GetAxis(angularAxis));

               // Create Twist message
               Twist twist = new Twist(
                    new Vector3(linearVel.x,
    linearVel.y, linearVel.z),
                    new Vector3(angularVel.x,
    angularVel.y, angularVel.z)
               );

               // Publish the message
               rosSocket.Publish(topicName,
    twist);
          }
     }
}
```

Listing 4: JoystickPublisher.cs

Appendix C.4.3. Message Example

```
//Do not edit! This file was generated by
    Unity-ROS MessageGeneration.
using System;
using System.Linq;
using System.Collections.Generic;
using System.Text;
using Unity.Robotics.ROSTCPConnector.
    MessageGeneration;
using RosMessageTypes.Std;

namespace RosMessageTypes.Sensor
{
     [Serializable]
     public class ImageMsg : Message
     {
          public const string k_RosMessageName
     = "sensor_msgs/Image";
          public override string
    RosMessageName => k_RosMessageName;

          //  This message contains an
    uncompressed image
          //  (0, 0) is at top-left corner of
    image
          //
          public HeaderMsg header;
          //  Header timestamp should be
    acquisition time of image
          //  Header frame_id should be
    optical frame of camera
          //  origin of frame should be
    optical center of camera
          //  +x should point to the right in
    the image
          //  +y should point down in the
    image
          //  +z should point into to plane of
     the image
          //  If the frame_id here and the
    frame_id of the CameraInfo
          //  message associated with the
    image conflict
          //  the behavior is undefined
          public uint height;
          //  image height, that is, number of
     rows
          public uint width;
          //  image width, that is, number of
    columns
          //  The legal values for encoding
    are in file src/image_encodings.cpp
```

```
        //  If you want to standardize a new
 string format, join
        //  ros-users@lists.sourceforge.net
and send an email proposing a new
encoding.
        public string encoding;
        //  Encoding of pixels -- channel
meaning, ordering, size
        //  taken from the list of strings
in include/sensor_msgs/image_encodings.h
        public byte is_bigendian;
        //  is this data bigendian?
        public uint step;
        //  Full row length in bytes
        public byte[] data;
        //  actual matrix data, size is (
step * rows)

        public ImageMsg()
        {
            this.header = new HeaderMsg();
            this.height = 0;
            this.width = 0;
            this.encoding = "";
            this.is_bigendian = 0;
            this.step = 0;
            this.data = new byte[0];
        }

        public ImageMsg(HeaderMsg header,
uint height, uint width, string encoding
, byte is_bigendian, uint step, byte[]
data)
        {
            this.header = header;
            this.height = height;
            this.width = width;
            this.encoding = encoding;
            this.is_bigendian = is_bigendian
;
            this.step = step;
            this.data = data;
        }

        public static ImageMsg Deserialize(
MessageDeserializer deserializer) => new
 ImageMsg(deserializer);

        private ImageMsg(MessageDeserializer
 deserializer)
        {
            this.header = HeaderMsg.
Deserialize(deserializer);
            deserializer.Read(out this.
height);
            deserializer.Read(out this.width
);
            deserializer.Read(out this.
encoding);
            deserializer.Read(out this.
is_bigendian);
            deserializer.Read(out this.step)
;
            deserializer.Read(out this.data,
 sizeof(byte), deserializer.ReadLength()
);
        }

        public override void SerializeTo(
MessageSerializer serializer)
        {
            serializer.Write(this.header);
            serializer.Write(this.height);
            serializer.Write(this.width);
            serializer.Write(this.encoding);
            serializer.Write(this.
is_bigendian);
            serializer.Write(this.step);
            serializer.WriteLength(this.data
);
            serializer.Write(this.data);
        }

        public override string ToString()
        {
            return "ImageMsg: " +
            "\nheader: " + header.ToString()
 +
            "\nheight: " + height.ToString()
 +
            "\nwidth: " + width.ToString() +
            "\nencoding: " + encoding.
ToString() +
            "\nis_bigendian: " +
is_bigendian.ToString() +
            "\nstep: " + step.ToString() +
            "\ndata: " + System.String.Join(
", ", data.ToList());
        }

#if UNITY_EDITOR
        [UnityEditor.InitializeOnLoadMethod]
#else
        [UnityEngine.
RuntimeInitializeOnLoadMethod]
#endif
        public static void Register()
        {
            MessageRegistry.Register(
k_RosMessageName, Deserialize);
        }
    }
}
```

Listing 5: ImageMsg.cs

```
# This message contains an uncompressed
    image
# (0, 0) is at top-left corner of image
#

Header header        # Header timestamp
    should be acquisition time of image
                     # Header frame_id
    should be optical frame of camera
```

```
                     # origin of frame
    should be optical center of camera
                     # +x should point to
    the right in the image
                     # +y should point down
    in the image
                     # +z should point into
    to plane of the image
                     # If the frame_id here
    and the frame_id of the CameraInfo
                     # message associated
    with the image conflict
                     # the behavior is
    undefined

uint32 height          # image height, that
    is, number of rows
uint32 width           # image width, that is
    , number of columns

# The legal values for encoding are in file
    src/image_encodings.cpp
# If you want to standardize a new string
    format, join
# ros-users@lists.sourceforge.net and send
    an email proposing a new encoding.

string encoding        # Encoding of pixels
    -- channel meaning, ordering, size
                       # taken from the list
    of strings in include/sensor_msgs/
    image_encodings.h

uint8 is_bigendian     # is this data
    bigendian?
uint32 step            # Full row length in
    bytes
uint8[] data           # actual matrix data,
    size is (step * rows)
```
Listing 6: Image Message in native ros .msg format