CyPhER: A Digital Thread Framework Towards Human-Systems Symbiosis

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Abstract

Cyber-physical twinning is an important area of study across multiple diverse fields. Creating more symbiotic human-machine partnerships facilitates extended reality. This thesis presents a flexible digital thread framework, CyPhER (**Cy**ber **Ph**ysical **E**xtended **R**eality), as a platform and application agnostic solution for human-systems symbiosis. This framework includes software, techniques, and a reference architecture to allow for implementation in any field where cyber-physical twinning is possible.

This thesis contains case studies carried out with industry partners in the domains of vocational education and robotics. These case studies demonstrate extended reality enabling human-systems symbiosis within their fields. When moving between these fields, CyPhER itself evolved, improving in terms of performance and capability. These applications required CyPhER to be deployed on a range of platforms spanning operating systems and form factors, which influenced its performance across these devices. Having flexibility in this approach allows CyPhER to address barriers in terms of computing apparatus in each field, such as edge devices.

A cyber-physical extended reality is beneficial as a teaching aid, supporting a symbiotic process where both students and tutors can benefit from a teaching environment which utilises both the real and virtual worlds. It also benefits the field of automation, allowing for a symbiotic partnership between the human operator and systems. This is achieved through bidirectional interactions between robots and humans to enable enhanced operational decision support. Approaching these applications with a cyber-physical solution has enabled gains in usability, flexibility, and scalability in each field, abstracting complex systems with extended reality features to enable symbiosis between systems and the humans that control them. This is demonstrated in the consideration of control display gains in human-system interaction, which addresses the interaction barrier between the human and the system.

Dedication

This thesis is written in dedication to Robert Kenneth Harper.

Acknowledgements

- To my wife, Haleigh
- To my family, mum, dad, Robert
- To my supervisor, Theodore Lim
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List of Abbreviations

- AID – Asset Integrity Dashboard
- AR – Augmented Reality
- BVLOS – Beyond Visual Line Of Sight
- CAD – Computer Aided Design
- CD – Control-Display
- CPS – Cyber-Physical System
- CPU – Central Processing Unit
- CyPhER – Cyber-Physical Extended Reality
- DT – Digital Twin
- FBX – Filmbox
- FMCW – Frequency Modulated Continuous Wave
- GPU – Graphics Processing Unit
- MR – Mixed Reality
- OBJ – Wavefront Object
- OS – Operating System
- ODSI – Operational Decision Support Dashboard
- PC – Personal Computer
- ROS – Robot Operating System
- SDK – Source Development Kit
- SSOSA – Symbiotic System Of Systems Approach
- SUS – System Usability Scale
- TCP – Transmission Control Protocol
- UAV - Unmanned Aerial Vehicle
- UDP – User Datagram Protocol
- USB – Universal Serial Bus
- UWP – Universal Windows Platform
- VET – Vocational Education and Training
- VLE – Virtual Learning Environment
- VR – Virtual Reality
- WLAN – Wireless Local Area Network
- XR – Extended Reality

List of Publications

Journal

1. Daniel Mitchell, Jamie Blanche, Osama Zaki, Joshua Roe, Leo Kong, Samuel Harper, Valentin Robu, Theodore Lim and David Flynn, *"Symbiotic System of Systems Design for Safe and Resilient Autonomous Robotics in Offshore Wind Farms"* [1]
   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout
   - Figure creation
     - Figure 2
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     - Symbiotic interactions (joint with Mitchell, Blanche, Lim, Flynn)
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     - Demonstration plan (joint with Mitchell, Blanche, Lim, Flynn)
     - Asset Integrity Dashboard (joint with Mitchell, Blanche)
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     - Use of mixed reality
     - Digital Twin stages
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     - Ghosting function (joint with Kong and Roe)
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     - Asset Integrity Dashboard.
   - Text
     - III. A. (specifically examples of symbiosis)

    - IV. (joint with Mitchell)
    - V.
    - VI. B.
    - All algorithms

2. Daniel Mitchell, Jamie Blanche, Sam Harper, Theodore Lim, Ranjeetkumar Gupta, Osama Zaki, Wensho Tang, Valentin Robu, Simon Watson and David Flynn, *"A Review: Challenges and Opportunities for Artificial Intelligence and Robotics in the Offshore Wind Sector"* [2]

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3. Theodore Lim, Mathis Linnenbrink, James Ritchie, Aparajithan Sivanathan, Sam Harper, Carsten Teichert and Anthony Waller, *"An industrial case study on discrete event modelling of value stream mapping for Industry 4.0"* [3]

   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout

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Contributions:

- Editorial (formatting, proofing, grammar, rewording, etc.) – throughout

5. Alice M Harper, Elizabeth Wastnedge, Aparajithan Sivanathan, Aileen Jordan, Samuel Harper, Theodore Lim and Fiona C Denison, *"Virtual reality as a distraction therapy in obstetrics and gynaecology"* [5]
   Contributions:
   - Conceptualisation
     - Use of extended reality technologies
   - Development
     - Development of applications used for extended reality testing

Conference

1. Sam Harper, Aparajithan Sivanathan, Theodore Lim, Scott Mcgibbon and James M Ritchie, *"Development of a Mixed Reality Game for Simulation Based Education"* [6]*
   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout
   - Figure creation – all unless cited otherwise excluding figures 9 and 10.
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     - VET usage (joint with Lim, Sivanathan and Mcgibbon)
     - Application concept (joint with Lim, Mcgibbon)
   - Development
     - Application development
   - Text - all
2. Sam Harper, Aparajithan Sivanathan, Theodore Lim, Scott Mcgibbon and James M Ritchie, *"Control-Display Affordances In Simulation-Based Education"* [7] *
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   - Figure creation – all unless cited otherwise
   - Conceptualisation
     - Testing methodology (joint with Lim, Sivanathan)
   - Development
     - Application development
   - Text - all

3. Leo Chi Wai Kong, Sam Harper, Daniel Mitchell, Jamie Blanche, Theodore Lim and David Flynn, "*Interactive Digital Twins Framework for Asset Management Through Internet"* [8]

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   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout
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   - Conceptualisation
     - Use cases
     - Digital Twins to monitor and control physical assets
   - Development
     - Fan application development
     - Husky digital twin development
   - Text
     - II. (main body)
     - III.

4. Osama Zaki, David Flynn, Jamie Blanche, Joshua Roe, Leo Kong, Daniel Mitchell, Theodore Lim, Sam Harper and Valentin Robu, "*Self-Certification and Safety Compliance for Robotics Platforms"* [9]

   Contributions:

   - Figure creation
     - Figure 12
     - Figure 13
   - Conceptualisation
     - Digital Twins in the context of self-certification and safety compliance
     - Use of mixed reality
   - Development
     - Digital Twin application
     - Mixed reality application
   - Text

        - Digital Asset Management and Operational Decision Support

5. Sam Harper, Shivoh Nandakumar, Daniel Mitchell, Jamie Blanche, Theodore Lim and Davd Flynn, *"Addressing Non-Intervention Challenges via Resilient Robotics utilizing a Digital Twin"* [preprint] [10] *

   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout
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6. Jamie Blanche, Shivoh Nandakumar, Daniel Mitchell, Samuel Harper, Keir Groves, Andrew West, Barry Lennox, Simon Watson, David Flynn and Ikuo Yamamoto, *"Millimeter-Wave Sensing for Avoidance of High-Risk Ground Conditions for Mobile Robots"* [preprint] [11]

   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout
7. Daniel Mitchell Daniel Mitchell, Jamie Blanche, Samuel Harper, Theodore Lim, Valentin Robu, Ikuo Yamamoto and David Flynn, *"Millimeter-wave Foresight Sensing for Safety and Resilience in Autonomous Operations"* [preprint] [12]

   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout

Book Chapter

1. James Ritchie, Theodore Lim, Aparajithan Sivanathan, Avery Read, Sam Harper, Scott McGibbon, Hugo I. Medellin-Castillo and Germanico González-Badillo, *"Virtual Environment Applications for Front-End Design and Manufacturing Planning Applications"* [13]

   Contributions:
   - Editorial (formatting, proofing, grammar, rewording, etc.) – throughout

2. Alistair McConnell, Daniel Mitchell, Karen Donaldson, Sam Harper, Jamie Blanche, Theodore Lim, David Flynn and Adam Stokes, *"The Future Workplace: A Symbiotic System of Systems Environment"* [14]

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     - SSOSA (joint with Mitchell, Blanche, Lim, Flynn)
     - Demonstration plan (joint with Mitchell, Blanche, Lim, Flynn)
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     - Asset Integrity Dashboard.
   - Text
     - 4.2 (teleoperation – digital twin simulation)
     - 5.2

*Primary author

1 Introduction

Cyber-physical twinning is the interaction between cyber twins and physical twins [15]. A twin in this context is an equivalent digital or physical version of a real-life object, which imitates its state. This differs from other twins which focus on a purely cyber forms or purely physical forms, facilitating one-way communication and interaction. It is an important aspect of digitalisation across industry and education. A digital thread performs the link between the cyber and real-world space through the transmission of infrastructure information [16]. This thesis presents a platform, application and data agnostic, interoperable digital thread framework for enabling human-systems symbiosis in cyber-physical twins. Within this thesis, a reference architecture is included to enable implementation within such applications. To determine its fitness for purpose and generalisation, the proposed CyPhER (***Cy***ber ***Ph***ysical ***E***xtended ***R***eality) framework will undergo a series of case studies. These will verify the system is built correctly, validate the correct system was built, and evaluate the usefulness of the system. Quantitative and qualitative analyses have been conducted on CyPhER, to discuss the relationship between the cyber and physical spaces. This is achieved through the computational networks designed and employed to achieve the thread between the cyber and physical spaces.

1.1 Thesis Contributions

This thesis makes the following major contributions:

- Presents a digital thread framework that is generalisable to a wide range of controls, workflows, and human-machine systems applications. The CyPhER framework includes a cyber-physical twin reference architecture and techniques for interactions, data transfer and system integration. This can be used for the design of cyber-physical twins, accounting for the necessary subcomponents, with techniques for interactions, data transfer and system integration. Using this reference architecture ensures symbiosis in the human-system interaction.
- Demonstrates the flexibility of CyPhER through the three diverse case studies. Each case study was driven by research and industrial demand. The individual case studies include novel cyber-physical twin implementations in vocational education, using mixed reality power tool training. Also covered is the energy sector, through cyber-physical twinning of a robotic fleet to enable symbiotic interactions.

- Each case study demonstrates how CyPhER was applied to address a challenge in their own domain, applying extended reality, cyber-physical learning to vocational education and human-systems symbiosis in digital twins, and how the case studies themselves served as a mechanism to improve and build upon CyPhER, allowing learnings to be applied in another field.

1.2 Hypothesis

A working hypothesis throughout the research is:

Human-system symbiosis can be enhanced by extended reality through a generalised digital thread framework that facilitates cyber-physical twinning.

Research has witnessed the rise of advanced human-machine systems, with the majority focusing on automation or adaptability of humans in situ. Today, we still query answers politically, ethically and scientifically to fundamental questions around the structures of human daily activities, be it for work, education, social and rest, and especially the role of humans within systems when the advancement of digitalisation transpires.

Complete autonomy without a human in the loop does not yet exist for a vast number of systems and complex tasks. Additionally, the creation of such systems still relies on the input of humans. Therefore, it is important that we consider the interactions of humans and systems. To achieve symbiosis in a human-systems approach enables both parties to work as one, elevating their overall capabilities. A digital thread is a critical component of human-systems interactions, connecting infrastructural information to real world environments. Therefore, we must consider a framework to enable such interactions. A challenge exists in standardising or creating symbiosis across a diverse range of systems, hence the requirement for a general framework which can be extended and modified to the needs of each system it is used in.

The aim of this work is to prove that the digital thread framework (CyPhER) presented herein enhances human-system symbiosis. This will be verified through the following:

- A literature review to identify the gaps in knowledge relating to the use of cyber-physical twinning in the fields of vocational education and offshore energy.
- Presentation of the proposed framework.
- Application of CyPhER in two industry-backed scenarios to prove its flexibility and interoperability.

- Identify the novel application of CyPhER in these studies for enabling the produced application.
- Present metrics to showcase data transfer performance.
- Suggest areas of future work with CyPhER to develop it yet further.

1.3 Digital Thread Framework

The following sections will define what is meant by the terms “digital thread,” “extended reality,” “cyber-physical twinning” and “human-systems symbiosis.” The literature review will investigate these terms in relation to CyPhER.

1.3.1 Digital Thread

Digital thread has been defined as “the use of digital tools and representations for design, evaluation, and life cycle management” [17]. Using this definition, this work uses the term digital thread to represent the interlinking of the physical and digital worlds, with a constant two-way flow of information over the lifetime of an asset. The interlinking is implemented in conceptual and practical terms, covering both the lifecycle management aspect and the protocols, processes and tools which connect both worlds. This information informs both the behaviour of the asset, and conceptualisation of a future asset. A graphical description is provided in Figure 1. The thread (denoted by the arrows) is used to link the information in a data driven architecture. It links the physical and digital aspects of a system.

Digital thread frameworks are still a burgeoning area of technology. PTC cites digital threads as “transforming how products are engineered, manufactured and serviced” [18].

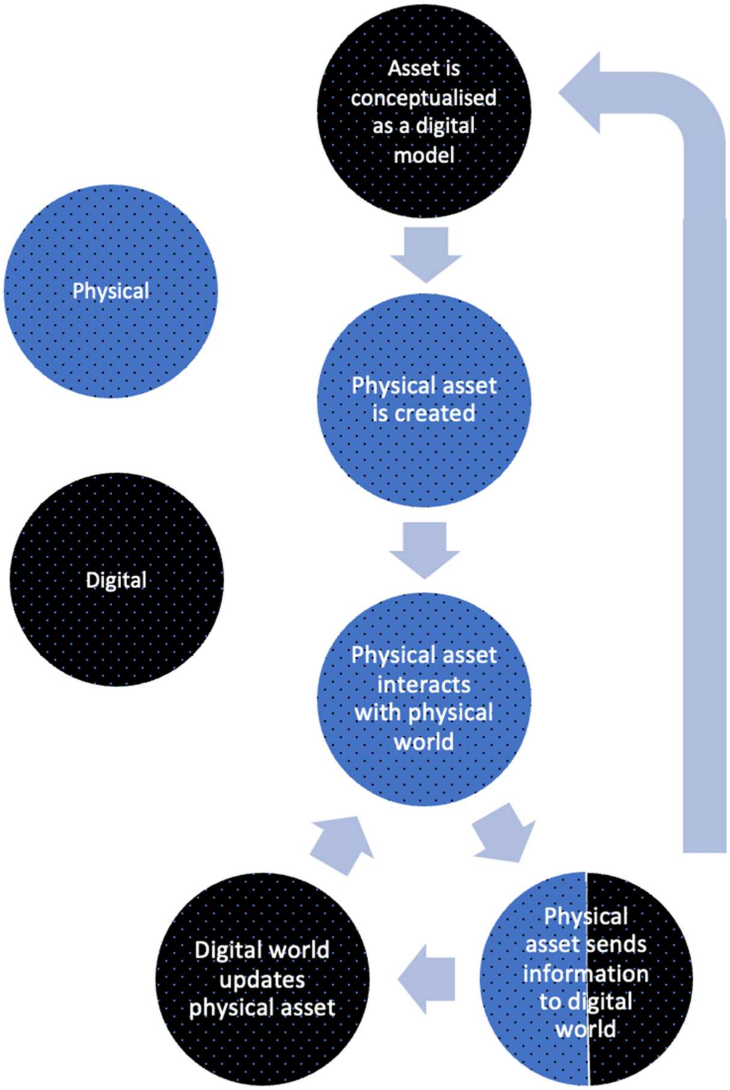


Figure 1: Graphical explanation of a digital thread.

A further description of the concept is provided in Figure **2**, which demonstrates the relationship between a digital and physical twin and how a digital thread facilitates this collaboration.

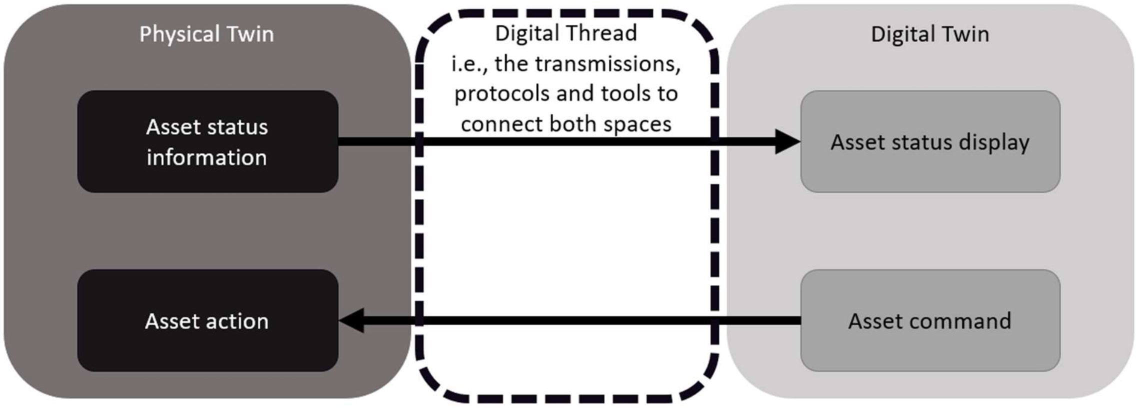


Figure 2: The role of the digital thread in a digital-physical twin system.

1.3.2 Extended Reality

Briefly, extended reality (XR) is a catch-all term for various reality-extending technologies and techniques: augmented reality, virtual reality and mixed reality [19]. Extended reality is explained fully in 2.3 Extended Reality.

1.3.3 Cyber Physical System

A Cyber Physical System (CPS) is the meeting of the virtual space and tangible space together in one system [20]. Examples include medical monitoring devices, autopilot on aeroplanes and assisted driving in cars.

1.3.4 Cyber Physical Twinning

The integration of CPS and DTs leads to cyber-physical twinning, which enables full integration of the real and virtual worlds and enabling human interaction beyond that found in a DT. For the purposes of this research, the digital twin is defined as "digital replications of living as well as non-living entities that enable data to be seamlessly transmitted between the physical and virtual worlds" [21]. Physical twins are physical objects with attached sensors or monitoring to interact with the digital twin. The field of CPS has been developed through the advancement of both digital and physical twins. The earth-based twin of the Apollo 13 mission has been proposed by Ferguson [22] as the first instance of a digital twin, it can be argued that it is also the first instance of a cyber-physical twin. Here, a physical twin of the command module was used by a ground-based crew. Commands performed within this physical twin was processed by digital twin running simulations of various return trajectories. Using the systems in this way allowed a successful course to earth to be determined. This symbiotic use of twins in both the cyber and physical space enabled the successful safe return of the crew. This can be compared to purely digital twins, which do not rely on this physical connection.

In the context of this thesis, both the proposed VET training simulation (positionally tracked stone grinder interacting with digital environment "twinning" a real-world space) and digital twin framework (robotic platforms and sensors interacting with digital representations and information) are considered cyber-physical twins. These areas are distinct in their applications yet require a similar approach to tackling the problems therein. Both areas are cyber-physical in their nature, requiring the use of digital hardware and software to achieve objectives in the physical world. However, the use of CyPhER in these spaces does not implicitly guarantee its usability in other cyber-physical applications. For this, further fields should be examined.

1.3.5 Human-Systems Symbiosis

The term "Man-Computer Symbiosis" was first suggested in 1960 [23]. The difference between this concept and the previous "mechanically extended man" concept is the removal of the dependence of the human to perform all tasks and the machine simply supporting them. Instead, humans and machines work in partnership to achieve a common goal. Symbiosis is a term taken from the natural ecosystem. The Cambridge Dictionary defines symbiosis as "a relationship between two types of animal or plant in which each provides for the other the conditions necessary for its continued existence". In the context of a digital ecosystem, this means systems that work together for a mutually beneficial outcome. This is in opposition to a parasitic relationship, where one party will take from the other to ensure its own survival, to the detriment of the other. The challenge of human-machine symbiosis is increased by the addition of a systems approach. How can we design a system to be symbiotic as a whole? In terms of humans and systems together, this means that both the human and the system, which consists of a number of physical and cyber objects, will benefit from any interactions. This can be through, e.g., knowledge exchange (an operator shares its knowledge with a robotic platform and vice versa) and mission preservation (one robotic platform will use extra battery to ensure another robot has a clear path to complete the mission). Mitchell et al. performed a review on symbiotic systems, which demonstrated that previous systems have tended to only focus on cooperation or collaboration [2]. The proposed system for a digital twin ensures Cooperation, Collaboration and Corroboration (C^3) between all symbiotic relationships, digitalised underneath a single digital twin. Previous work on this aspect can be found at the following:

2020 IEEE Global Conference on Artificial Intelligence and Internet of Things [8], Offshore Technology Conference [9], IEEE Access [1] and Elsevier Energy and AI [2].

1.4 Thesis Structure

Following Chapter 1, the structure of this thesis, shown in Figure 3, begins with a literature review to identify the research gaps that this work aims to address. Then, the methodology explains the reference architecture and an overview of what CyPhER achieves. From herein, the work is structured in a chronological order, showing how CyPhER developed as the case studies progressed, with a more detailed description of what each case study involved. This progression is then highlighted in the Framework Metrics and Discussion chapter, and finally the conclusion and future work.

By structuring the thesis in this manner, it is intended that all contributions and addressed knowledge gaps will be clear, as will the development of CyPhER throughout the studies.

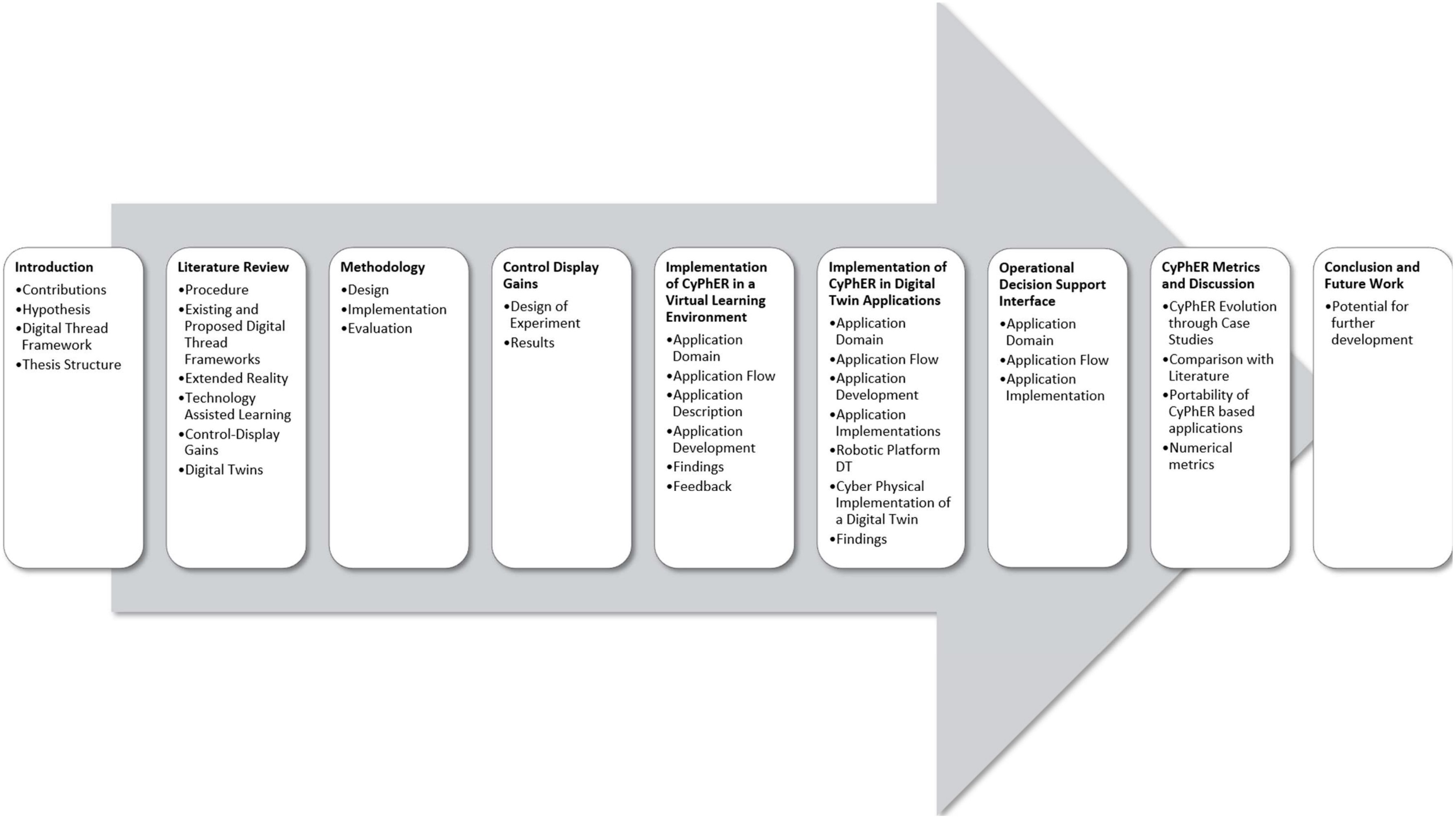


Figure 3: Thesis organisation

2 Literature Review

This chapter provides an overview of the current state of the art in digitalisation and digitisation towards cyber-physical twins. From this, it is possible to identify gaps within existing research, which are addressed by this work. The procedure to achieve this is laid out, and then a separate review for each area addressed in CyPhER. This is concluded by a summary of the gaps identified within this review.

2.1 Procedure for Literature Review

CyPhER was broken down into five areas of research for this review. These areas were chosen to capture the unique aspects of CyPhER. When combined, the research areas can be used to give an overview of the capabilities of CyPhER and the areas it aims to tackle. The shortcoming of this approach is the potential to miss other areas in which CyPhER is either not unique in its premise or can offer something new to these areas. To discover this in future, it will be necessary to perform reviews of broader areas of literature rather than restricting the search to specific areas.

Existing digital thread frameworks for cyber-physical twinning were reviewed and compared. Then, contemporary extended reality technologies, with comparisons on their capabilities. A comparison of existing technology assisted learning platforms is provided. This includes a review of existing implementations of technology assisted learning, on the viability of extended reality educational tools, and a comparison of contemporary digital learning research, categorising research based on what areas are addressed. Control-Display Gains are explained, with an explanation of desktop Control Display (CD) gains, the lack of existing research on CD gains in a mixed reality environment, and a review of limitations in mixed reality interaction. Continuing with the theme of human machine interaction, there is a review on digital twin technology. This includes a proposed categorisation of digital twins, existing digital twins in the energy sector, comparisons of selected existing digital twins and of proposed and existing twins in the offshore renewable energy sector. Despite the case studies being from two diverse fields in the energy and education sectors, there are in fact significant areas of commonality in the approach required. Figure 4 provides an overview of the attributes covered within each case study.

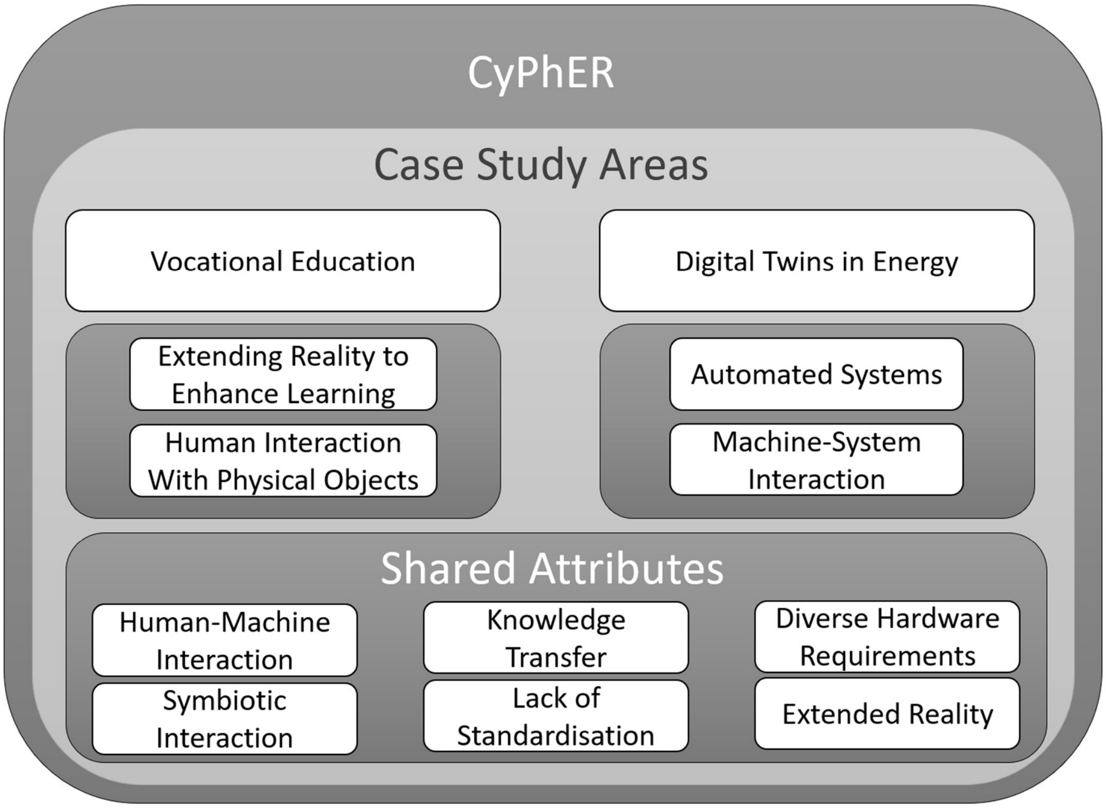


Figure 4: Identified CyPhER attributes.

Each section contains a broader review to confirm definitions of terminology used within this work and common technology in each area. Then, a review is performed in each area. The procedure carried out was as follows:

1. Broad keywords of each area determined (these are highlighted at the top of each table).
2. Keyword search of article titles and abstracts performed in Scopus, within the timeframe of the first published work in the field to the conclusion of 2022, unless otherwise noted. This considers only peer-reviewed journal papers. Exact keyword search strings are highlighted in each review. Scopus was used due to its availability within the Heriot-Watt systems, analysis tools and wide range of works covered when compared to the Heriot-Watt Discovery service. This means there is the potential for some relevant works to have been missed, but as Scopus carries 44,737 sources including all content indexed on IEEE Xplore it is likely most relevant articles have been accounted for.
3. To filter results further, only works with at least one citation are taken further. Self-citations are not accounted for in this filter, which means some works may have only

been cited by their authors. This leads to the possibility of low quality, non-peer-reviewed work having been assessed in this review, however as the filter is in place to remove most of these kinds of works to make the reviews more manageable, this is not seen as a major downfall.

4. Specific keywords identified from what this work aims to achieve in each field.
5. Papers searched for keywords, both for an exact match and for a contextual match.
6. Papers plotted in a matrix with the fields covered in each work.

Using this method, plotting the matrix highlights if any existing work covers all the fields explored and addressed in this work. This identifies gaps in research which can be covered by CyPhER and ensures its novelty in the field. In addition, plots of the broad keyword search are presented to identify the overall activity of research in each area over time.

2.2 Existing and Proposed Digital Thread Frameworks

A Scopus search of abstracts and titles for the keywords "digital thread" and "framework" shows that since the first instance in 2013, there have been 71 publications featuring these keywords. The trend in citations seen in Figure 5 shows increased research interest in the technologies.

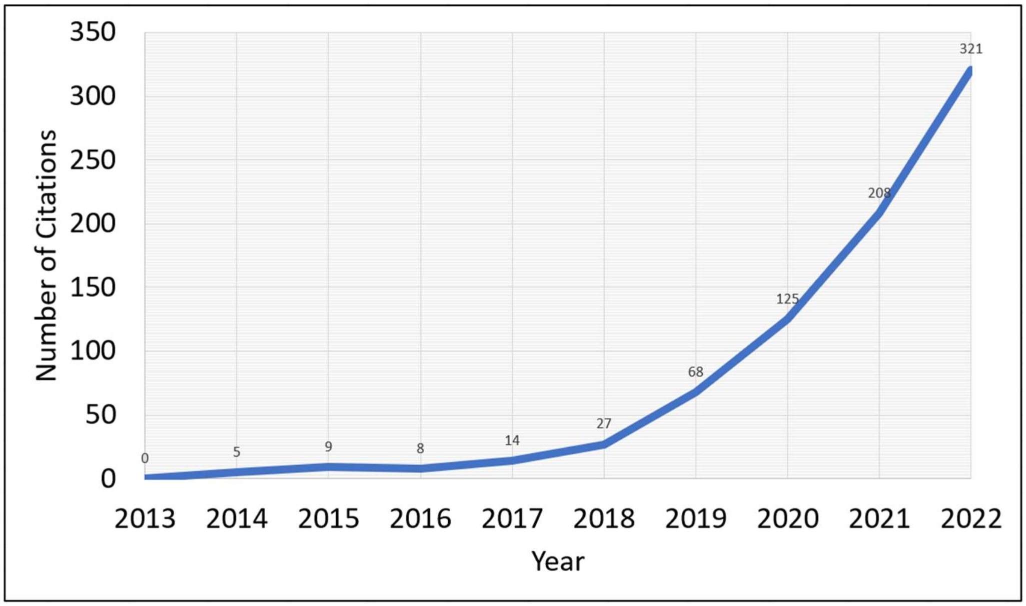


Figure 5: Digital Thread Framework citation overview from Scopus.

From these results, the following in Table 1 are the existing digital thread frameworks with at least one citation.

Table 1: Results from Scopus search for existing digital thread frameworks with at least one citation.

Ref	Digital Thread	Cyber Physical Twinning	Extended Reality	Symbiosis	Human-System Interaction
Kraft [24]	▒	▒	■	■	■
Singh [16]	▒	▒	■	■	■
Kraft [25]	▒	▒	■	■	■
Nassar [26]	▒	■	■	■	■
Bernstein [27]	▒	▒	■	■	▒
Wang [28]	▒	▒	■	■	▒
Li [29]	▒	■	■	■	■
Bone [30]	▒	▒	■	■	■
Kwon [31]	▒	■	■	■	■
Mourtzis [32]	▒	■	▒	■	▒
Pang [33]	▒	■	■	■	■
Zhang [34]	▒	▒	■	■	▒
Promyoo [35]	▒	▒	■	■	■
Felstead [36]					
Wärmefjord [37]	▒	▒	■	■	■
Reitenbach [38]	▒	▒	■	■	▒
Boddeti [39]	▒	■	■	■	■
Zhu [40]	■	■	■	■	■
Gharbi [41]	▒	■	■	■	■
Miled [42]	▒	▒	■	■	▒
Liao [43]	▒	▒	■	■	■
Mavris [44]	▒	▒	■	■	■
[45]	▒	▒	■	■	■
Mustafa [46]	■	■	■	■	■
D'Angelo [47]	▒	▒	■	■	■
Ravi [48]	■	■	■	▒	■
Orellana [49]	▒	■	■	■	■
Gaska [50]	▒	■	■	■	▒
Yasin [51]	▒	▒	■	■	■
Simpson [52]	▒	▒	■	▒	▒
Raju [53]					
Shukla [54]					

Key:
▒ Implemented
■ Not implemented
☐ Not available

As can be observed, no existing work on digital thread frameworks address all proposed areas. During the search, three works were found which were unavailable for viewing through the institution, Scopus or the publisher website. Of particular interest are the short proposal by Simpson [52], which proposes the "Digital Earth" as being the great technological achievement of the 21st century. While this proposal does not include any mention of extended reality, it is one of the few searched which addresses the issue of symbiosis. This comparison shows there is a gap in the research for a digital thread framework which extends reality through cyber-physical twinning, and addresses human-system symbiosis.

2.3 Extended Reality

This section examines the use of extended reality. The HoloLens, HoloLens 2 and Magic Leap are the first consumer-available devices within this space which enable mixed reality interaction. As these are prototype devices, there has not been a large amount of previous research. This gives opportunities to conduct new research in fields where this technology has not been previously accessible, to evaluate what impact such technology could have on these fields in the future.

To begin, it is important to define the various technologies referenced in this research. This section will define what is meant by Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) and give some examples of the currently relevant applications in each sector.

2.3.1 Virtual Reality

Bryson [55] presented the definition of virtual reality in 1998 as "the use of computer technology to create an effect of an interactive three-dimensional world in which the objects have a sense of spatial presence". VR in the context of this research is in reference to immersive virtual systems such as the HTC Vive and Oculus Rift, which conform to Bryson's definition of VR.

The arrival of the consumer versions of these two PC based devices in 2016 [56] [57], one week apart, defined the modern generation of affordable, accessible VR that can be used in the home [58] [59]. Both are based on similar technology, with both possessing a 90Hz display within a headset that does not allow for vision of the outside world, hence the term "immersive" [60]. Both devices require a sufficiently powerful PC to drive them and require cabling, alternatives now exist which do not have this constraint. A comparison of the headsets can be found in Table 2.

Table 2: Comparison of HTC Vive and Oculus Rift headsets

	HTC Vive [60]	Oculus Rift [61]
Display	2x AMOLED screen	2x AMOLED screen
Resolution	1080 x 1200 per eye	1080 x 1200 per eye
Refresh Rate	90Hz	90Hz
Field of View	110 degrees	110 degrees
Connections	HDMI, USB 2.0, stereo 3.5 mm headphone jack, Power, Bluetooth	HDMI, USB 3.0, stereo 3.5 mm headphone jack

Spatial presence is achieved for both by motion tracking through their respective controllers and the headset itself, although whilst the Vive allows for room-scale tracking whereby the user is free to move in an expansive 3D space, the Rift is designed around stationary experiences. This is due to the difference in tracking technology used, whereas the Vive uses "lighthouse" tracking which emits infrared (IR) lights which are received by the headset and controller IR sensors [62], the Rift uses its base stations to track the IR emitted by the headset and controllers [63]. Other than this difference, the two devices are functionally nearly identical, and indeed most software that works for one will work for the other. Both systems are incorporated into the OpenVR Application Programming Interface (API), in other words a set of premade functions which can be utilised by developers in their applications, which allows developers to target VR hardware from multiple vendors without knowing which headset is being specifically targeted [64]. An example of an immersive VR environment is shown in Figure 6.

Figure 6: User with a VR headset, with a display demonstrating their view of an immersive VR environment [Image credit: Reuters]

2.3.2 Augmented Reality

Craig [65] suggests the definition of augmented reality to be “a medium in which information is added to the physical world in registration with the world.” This is a broad definition of the term but is useful as a descriptor of the ideas of such a system. To be more precise, Azuma [66] details three defining characteristics:

1. Combines real and virtual
2. Is interactive in real time
3. Is registered in three dimensions

The distinction between AR systems and the previously discussed VR systems is the real environment is overlaid with interactive, 3-D components. The currently emerging popularisation of this approach is to be found on mobile phone handsets, with both Apple and Google developing APIs (ARKit [67] and ARCore [68] respectively) to take advantage of a phone’s camera and gyroscope to overlay virtual content onto real-world environments. The widespread consumer adoption of AR is a recent development, despite being possible for several years it is only in the last 5 years that the technology has seen a large push, with Apple's keynote at Worldwide Developer Conference 2018 providing examples of where the technology could be used across its range of iOS devices [69]. The surge in use of the technology is down to the now more widespread use of high-quality gyroscopes and cameras in mobile devices.

A distinct advantage AR has over VR is the possibility of collaboration in real space. An example of such an AR environment can be seen in Figure 7.

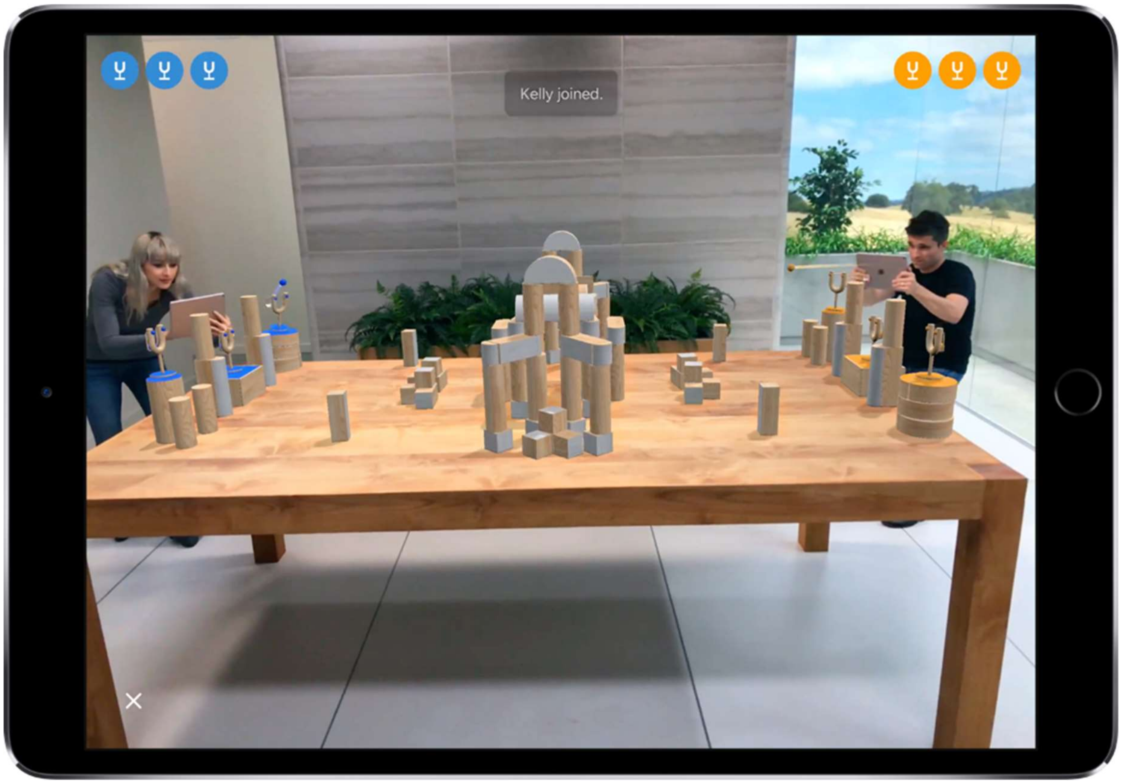


Figure 7: AR example [67] [Image credit: Apple Inc.]

2.3.3 Mixed Reality

Mixed Reality combines the principles of VR (the use of a headset, presence in a virtual space) and AR (the overlaying of virtual objects onto real space) to produce a different experience from the above. Microsoft, one of the leaders in MR technology, defines this as "the result of blending the physical world with the digital world" [70]. Milgram and Kishino [71] present the following Figure 8 as a descriptor.

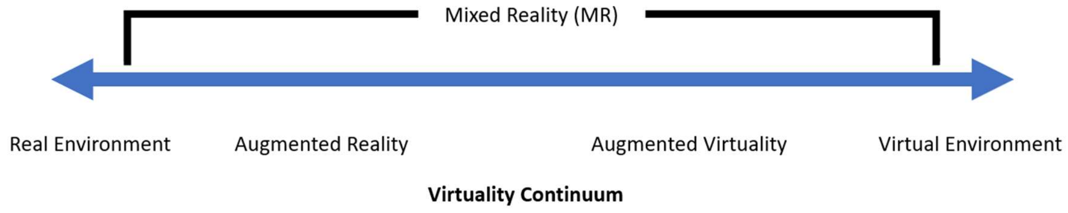


Figure 8: The position of MR in the "Virtuality Continuum" [71]

The "Virtuality Contunuum" (VC) is a scale across which all real and virtual reactions can be governed. The scale ranges from entirely virtual environments on the right, to the fully real environment on the left. MR is a blending of previously defined XR spaces. A major differentiation from VR is that to be considered MR, the outside world must be visible, but unlike AR the experience must be immersive, and not passive such as viewing the environment through a phone screen. Therefore, the typical MR device is a head-mounted display with translucent screens that can overlay virtual content. It is also critical for an MR device to understand the environment around it, so the typical MR device will also have environmental understanding capabilities, such as head tracking and spatial mapping (the representation of real-world surfaces in the environment [72]). These differences also have consequences for the interaction methodologies each level of virtuality can employ. With the outside world completely obscured it is possible to use tools such as teleportation which are not possible in the MR or AR spaces. Likewise it is not possible to utilise the physical world in a VR or AR environment in the same way as in MR. Visual representations of each degree of virtuality are demonstrated in Figure 9. Visual examples of headsets are shown in Figure 10.

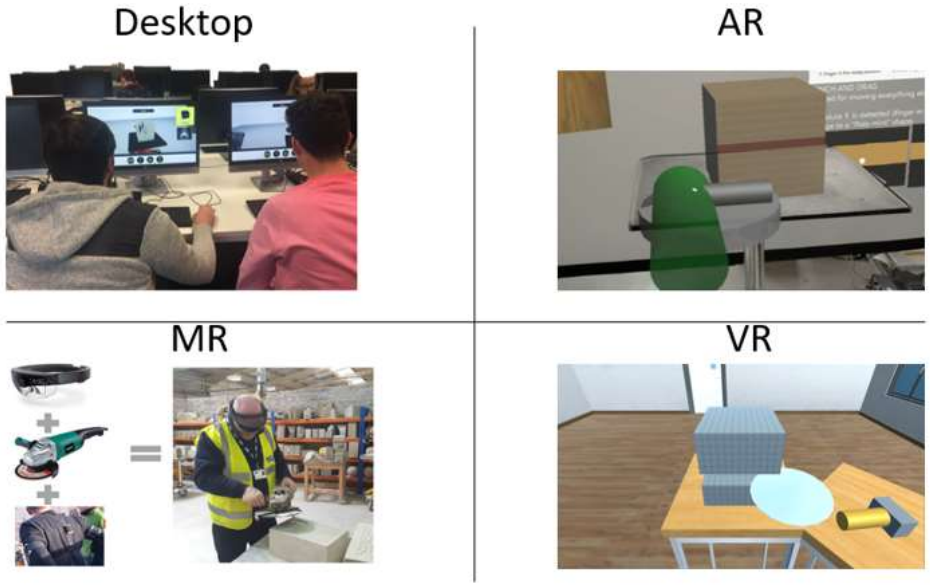


Figure 9: Examples of different points on the virtuality continuum.

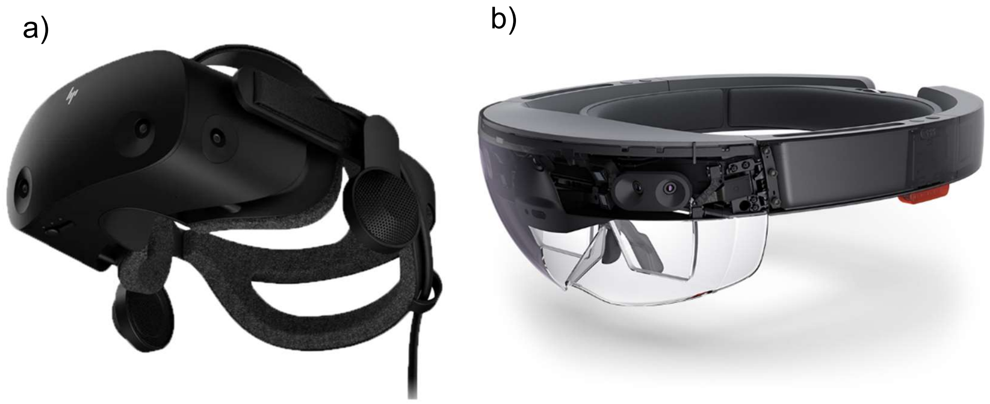


Figure 10: a) A typical VR headset, [image credit: vr-expert.io]. b) A typical MR headset [image credit: Microsoft]. Note the VR headset is occluded, while the MR headset has translucent displays.

Due to the rate of progress in display technology and graphical processing, true MR is a very recent development. At the time of writing, three widely supported MR devices are available, the Microsoft HoloLens (launched in 2015) [73], the Microsoft HoloLens 2 (launched in 2020) [74] and the Magic Leap One (ML1, launched in 2018) [75]. Unlike traditional VR headsets, all three devices are standalone and do not require a PC to operate. They all meet the generic MR description outlined above. A comparison of the devices can be found in Table 3.

Table 3: Comparison of HoloLens, HoloLens 2 and ML1

	Microsoft HoloLens [76]	**Microsoft HoloLens 2** [74]	**Magic Leap One** [75]
Central Processing Unit (CPU)	32-bit Intel Atom plus custom Holographic Processing Unit	64-bit ARM based Qualcomm Snapdragon 850 plus custom Holographic Processing Unit	64-bit Nvidia Parker System-On-Chip
Graphics Processing Unit (GPU)	Intel Integrated Chipset	Qualcomm Integrated Chipset	Nvidia Pascal
Random Access Memory (RAM)	2GB	4GB	4GB
Display	Two "waveguide" displays	Two "waveguide" displays	Two "waveguide" displays
Operating System	Windows 10	Windows 10	Custom
Weight (g)	579	566	345
Cost	USD 3,000	USD 3,500	USD 3,299

There are three major points of differentiation between the fundamentals of the three devices. Both HoloLens models perform all processing activities within the headset, whereas the ML1 has an external "Lightpack" on which all processing is performed, the headset is only a display. Whilst this has the advantage of making the device lighter (345g vs 579g), it does sacrifice some mobility due to the cabling present. Secondly, the HoloLens models uses gesture-based commands, whereas the ML1 uses a haptic remote. Whilst this ensures the desired input is always recognised properly, it again reduces the mobility of the device. Finally, the ML1 runs on a custom operating system, on which little documentation is available, whereas both HoloLens models uses Windows 10, which is already well documented due to its widespread use in desktop PCs. The 2020 release of the HoloLens 2 means it was released after most of the XR research contained within was carried out. It is for these reasons that the original HoloLens model is being used for this research.

2.4 Technology Assisted Learning

This section will focus on XR-CPS applicable to the education sector. This was conducted primarily for the purposes of the VET application. The focus is on the use of technology enhanced learning.

2.4.1 Technology Assisted Learning

Technology assisted learning is a well-developed field in pedagogy. Computer-based training has existed for decades and is widely used across industry, from the immersive nature of aviation training [77] [78] to more traditional multimedia based training, which can both be found in industry and educational sectors, such as Heriot Watt University's own VISION system [79].

A 2005 study carried out by Chittaro and Ranon [80] explores the use of computer games as an educational tool through their use of Web3D technologies, which are used to display 3D content on websites. The study lists some advantages and disadvantages of using such technologies in education for creating educational virtual environments (EVEs).

Highlighted advantages of using EVEs listed include using them to provide experiences which are impossible to reconstruct in the real world due to factors such as cost, safety and impracticality. This is an important component of the VET case study, due to the inability of the college students to use the equipment and techniques covered in the VET application in real life. Another advantage listed is that of multiple viewpoints for analysing the same subject. This reaffirms one of the aims of CyPhER, to provide the ability to view operations and processes from different points of view for purposes of analysis and feedback.

The study does highlight some still-relevant issues relating to the use of immersive VR HMDs, particularly that of the inability to follow instructions and take notes when in the EVE. This is covered in the research of Dede et al. [81], which specifically cites factors such as low display resolutions, limited tracking with latency, limited haptic feedback, cumbersome physical interfacing, and the sensation of feeling lost as contributing aspects. Whilst some of these aspects have improved greatly since the papers' 1999 publication, such as the display resolution, or at least mitigated in the case of physical interfacing through the widespread adoption of wireless control interfaces, some other aspects still prove problematic in the field of VR development. Specifically related to pedagogy, there is the risk of producing misconceptions about the content represented on the system through inaccurate manipulation of audio, visual and tactile cues, which hinders the impact of the learning delivered. This is especially critical in the field of VET, where safe work practices must be instilled from the start due to the innate hazards of working with power tools.

2.4.2 Viability of Extended Reality as Educational Tools

The use of extended reality technologies in the field of digital pedagogy is still rapidly developing with the introduction of VR to the mainstream through devices like the Oculus Rift or HTC Vive.

Wickens, a recurring source in the field of digital pedagogy through VR, presented an overview study on virtual reality in education [82]. In this, it is presented that through the presence of four justifications for the costs of VR: motivational value, transfer of the learning environment, a novel perspective, and a natural interface. These are all vital components of the proposition of the use of MR in this research, especially the points on the natural interface and the motivational value. In the VET environment, it was backed up by the results obtained in section 5.5, where it was found that the students found the novel use of MR motivating and pointed out the importance of having a natural interface, which is presented in the application using real tools. The study points to the importance of “good interface design” and “the reduction of effort”, which also ties into the research carried out into control display gain.

Dede et al. [81] presented that the use of VR allowed students to better describe, define and demonstrate complex scientific concepts in their study. Specifically, the grasping of concepts in 3D space was enhanced. Whilst this research does not specifically tie into VET, it is useful knowledge for further applications of CyPhER and reaffirms the use of these novel technologies in a learning space due to the heightened understanding achieved by the students in the study. This study also touches on the effects of “simulator sickness” which may have to be considered in future.

Sivanathan et al. covered the use of a cyber-physical gaming system to simulate a ladder climbing activity [83]. Sensors were attached to the participant to monitor their movements and posture throughout the activity. Gamification was enabled by a scoring system for how well a user kept a biomechanically safe posture throughout the procedure.

Limitations to the adoption of these technologies in this space can be found in the maturity of the hardware available. Related to this are cost and ergonomics. While costs for purchasing the hardware are decreasing as time moves forward, individual MR devices especially are still 3-4x the cost of individual laptops for a classroom. This is before the availability of laptops as a service product are considered against the scarcity of MR devices. Ergonomically, standalone XR devices are hindered by increased weight and limited battery life which affects their long-term use when worn compared to headsets which rely on external processing. Conversely the cables found in wired devices present classroom hazards such as tripping, strangulation and restrict a student's freedom of movement. XR devices are also currently not equipped for use by people with accessibility needs, such as missing limbs or cognitive impediments, which further limits their use in the classroom in their current state.

2.4.3 Safety Issues in Vocational Education

A major safety issue in vocational education is the lack of provision for usage of a real power tool in Scottish further education courses. This means there is no way for a student to practice power tools safely in a controlled environment, as of 2018 power tool safety was carried out as a classroom, pen-and-paper-based exercise. According to the Health and Safety Executive, the construction industry, which sees extensive use of power tools, has an injury rate which is "statistically significantly higher" than the "all industries rate" in the UK in 2021, and was second overall for workplace injury rate behind the agriculture, forestry and fishing sector, which also sees power tool usage [84]. Therefore, it is critical that safe working practices are instilled in students during their education, rather than relying on the working environment being their first exposure to power tool usage.

2.4.4 Contemporary Digital Learning Research

The review of contemporary literature was carried out using the following criteria listed in Table 4. The keywords chosen were "Mixed Reality Learning". The 24 papers produced were categorised by their features, this is shown in Table 4.

Table 4: Results of literature search and comparison of existing Mixed Reality Learning techniques

Ref	Technology assisted learning	MR/AR	VR	Collaboration	VET	Other Training	Data Synchronisation
Kurilovas [85]	░	░	░	▓	▓	░	▓
Johnson-Glenberg [86]	░	░	▓	░	▓	░	▓
Fotouhi-Ghazvini [87]	░	░	▓	▓	▓	░	▓
Emmerich [88]	░	░	▓	▓	▓	░	▓
Guo [89]	▓	▓	▓	▓	░	▓	▓
Chittaro [80]	░	▓	▓	▓	░	░	▓
Dalgarno [90]	░	▓	▓	▓	▓	▓	▓
Pan [91]	░	░	░	░	▓	▓	▓
Lindgren [92]	░	░	▓	▓	▓	▓	▓
Monahan [93]	░	▓	░	░	▓	▓	░
Mikropoulos [94]	░	▓	░	▓	▓	▓	▓
Jang [95]	░	▓	░	▓	▓	▓	▓
Huang [96]	░	▓	░	▓	▓	▓	▓
Sirakaya [97]	░	░	▓	▓	░	▓	▓
Hughes [98]	░	░	░	▓	▓	░	▓
Müller [99]	░	░	▓	░	▓	░	▓
Gu [100]	░	░	▓	░	▓	▓	░
Martinazzo [101]	░	▓	░	░	▓	▓	▓
Wickens [82]	░	▓	░	▓	▓	▓	▓
Dede [81]	░	▓	░	▓	▓	░	▓
Economou [102]	░	▓	▓	░	▓	▓	▓
Valdez [103]	░	▓	▓	▓	▓	░	▓
Cowling [104]	░	░	░	▓	▓	░	▓
Tasker [105]	░	▓	▓	▓	▓	░	▓
Presented Work	░	░	░	░	░	░	░

Key: ░ Implemented
▓ Not implemented

The survey revealed no existing works addressed all areas of mixed reality learning which were addressed by the Beaconing project [106]. This also shows that there were at the time no extended reality, cyber-physical twin based vocational education simulations. Thereafter, there have been some publications of extended reality based digital learning applications. Notably, Wolf et al. [107] published a book chapter on designing augmented reality applications as learning activities, with further indications on how to make these applications engaging. This example used a gamified photo competition, which used virtual overlays on real world environments to, e.g., show the recyclable content of liquid storage containers. The authors of this work identified that despite this, the students preferred to learn in this interactive method as opposed to spending an equivalent amount of effort writing an essay. However, this study lacks an evaluation of the learning outcomes of this technique, so it cannot be known for certain how much the students learned compared to a paper-based exercise.

2.5 Control-Display Gains

In any computer-based environment, Control-Display (CD) gains are critical to intuitive interaction. These gains are essentially to compensate for movement range of an input device to move an object (e.g., a pointer on a desktop PC) on a display. Generally, operations by proxy such as this are not 1:1, rather using some ratio to generally amplify mouse movements. On PCs, this is a well explored subject due to the maturity of the systems, but on MR devices this is still relatively unexplored.

2.5.1 CD Gains in Desktop Environments

Casiez et al. [108] published a widely cited study on the importance of CD gains and their impact in pointing operations on a desktop PC. This study involved analysing the impact of various levels of CD gain on desktop PC usage. Desktop operating systems (OS) such as OSX and Windows dynamically adjust CD gain depending on device velocity, in a function known as pointer acceleration (PA). A simple demonstration of this is shown in Figure 11. The paper states previous studies into CD gain found that PA had a neutral to negative effect on user performance did not consider more modern, aggressive PA techniques, such as the "Enhance Pointer Precision" option found in Windows machines. The workings of this algorithm are not in the public domain. Such a system could prove especially beneficial to gesture-based interactions, particularly as arm fatigue is a factor.

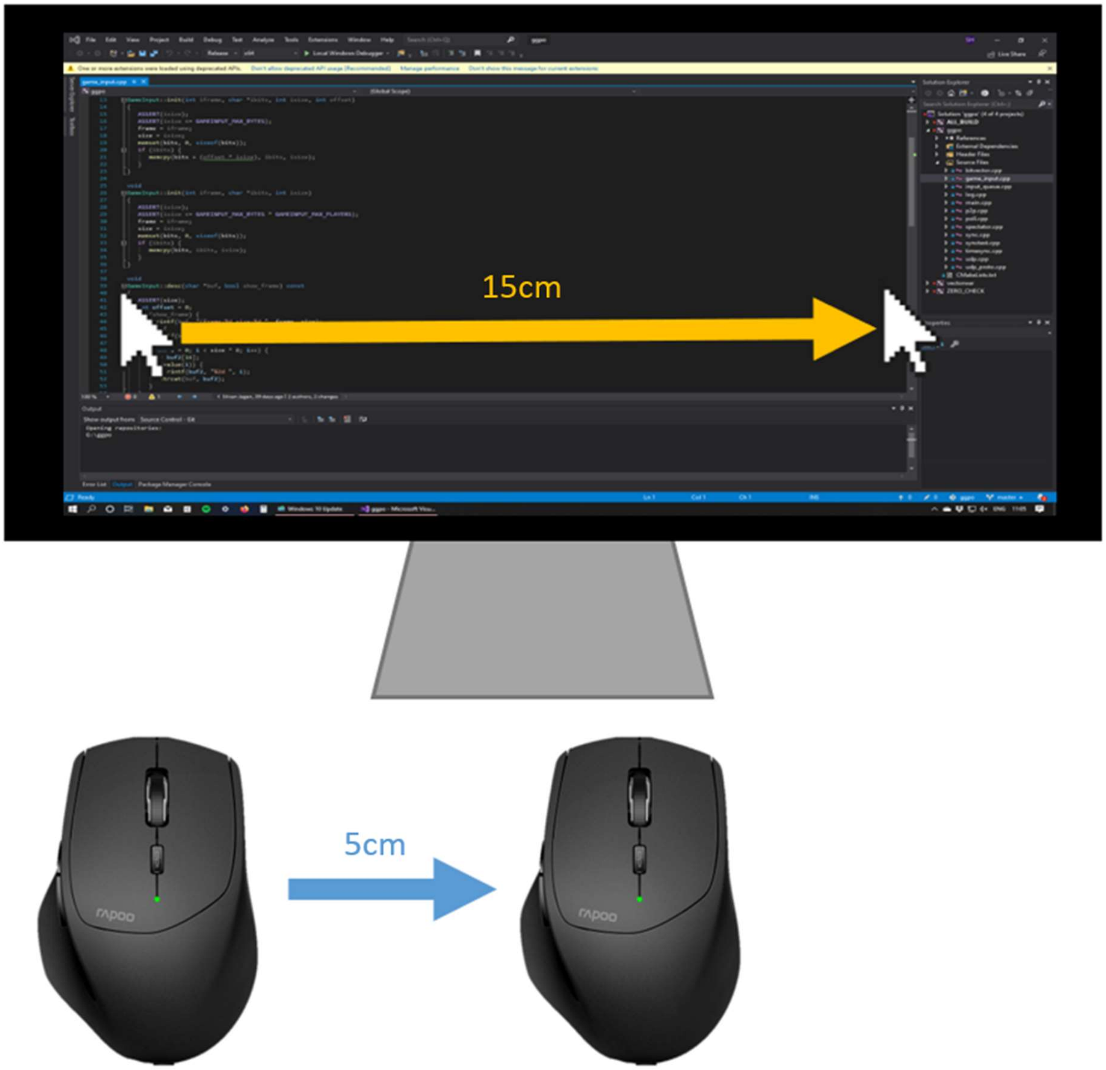


Figure 11: Diagram demonstrating PA

2.5.2 CD Gains in a Mixed Reality Environment

Conversely to the maturity of study into CD gains in traditional desktop systems, the analysis of such gains on a MR device such as a Microsoft HoloLens is lacking. The OS of the device does not use a PA technique, rather it uses a static value for all operations, with no adjustments made depending on application or type of movement. What separates the HoloLens from a more traditional, immersive VR system is the nature of the gesture-based controls. Immersive systems use tracked controllers for what are usually 1:1 operations, however there is still scope for some CD gain adjustment, due to the immersive nature of the headset obscuring the user's line-of-sight. An example of this manipulation is presented by Andersson [109], whereby a "Towers of Hanoi" game is utilised in conjunction with a varying CD ratio to measure the impact the variation had on both the time to complete, and the users' own perceptions on what was happening. This paper also mentions the concept of proprioception, which is a main point of difference between VR and MR systems. Due to the immersive nature of a VR system, it is not possible for the user to see where in space their hands are, whereas the translucent nature of the HoloLens display means it is not possible to alter perceptions in this fashion. This work does not explore the effects of dynamically variable CD gain in a pointer acceleration style, which is still a field that is not explored in XR space.

The HoloLens uses the hand as a proxy for manipulating virtual objects, much like a computer mouse. While selection of on-screen items is carried out through a gaze-and-press system, whereby the user looks at the desired item and performs a press gesture, or *air tap*, dragging of these items is performed by a pinch-and-hold gesture, where the movement of the hand dictates the movement of the item. This manipulation is used when an object needs free movement in 3D space. The drag and hold movement is demonstrated in Figure 12.

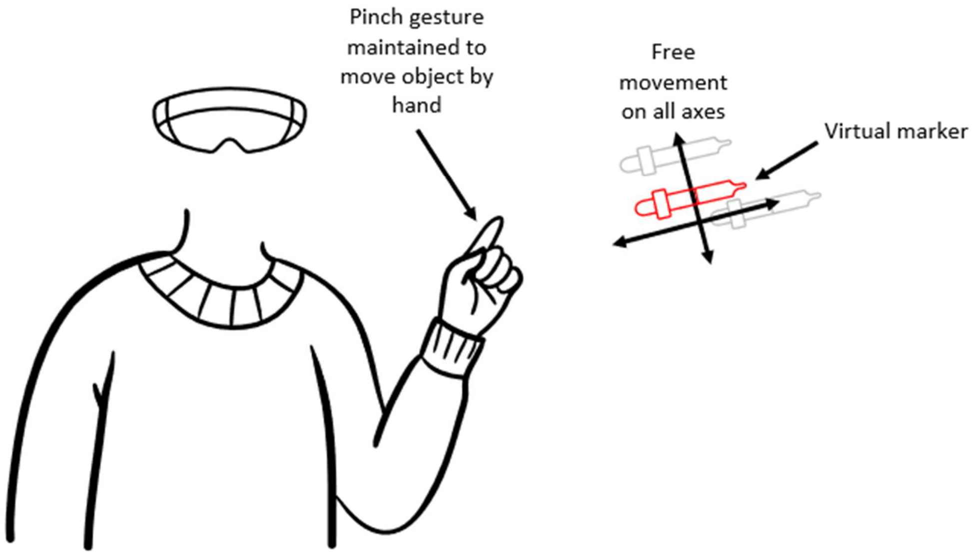


Figure 12: Manipulation of virtual objects via drag and hold.

An alternative input method is tap-to-place. In this case, the user performs the air tap gesture, which triggers control of the object. Movement of the object is now controlled by movement of the head, allowing the object to “snap” onto a surface. A second air tap ends the manipulation. This manipulation is primarily used when an object needs to be placed on top of another object or surface and then not moved. This is shown in Figure 13.

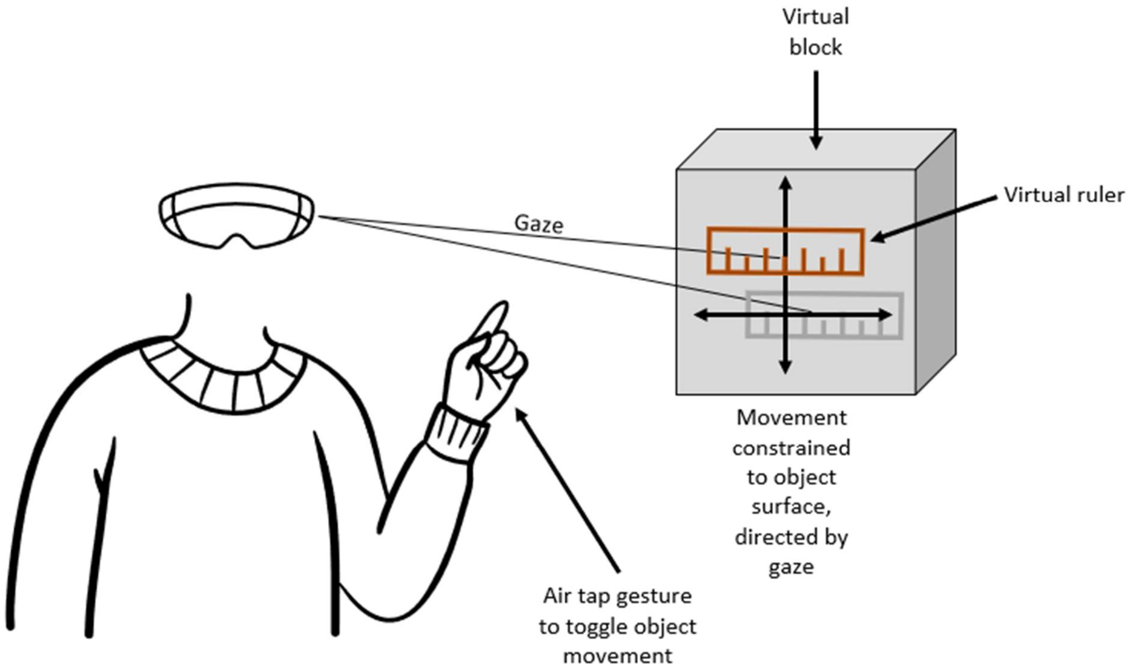


Figure 13: Manipulation of objects via tap-to-place.

A primary reason for the lack of 1:1 object grabbing is that immersive VR usually involves acting with an environment that is within arm's reach for the user, whereas the typical MR environment is placed somewhere between 2 and 5 metres from the user [110], demonstrated in Figure 14.

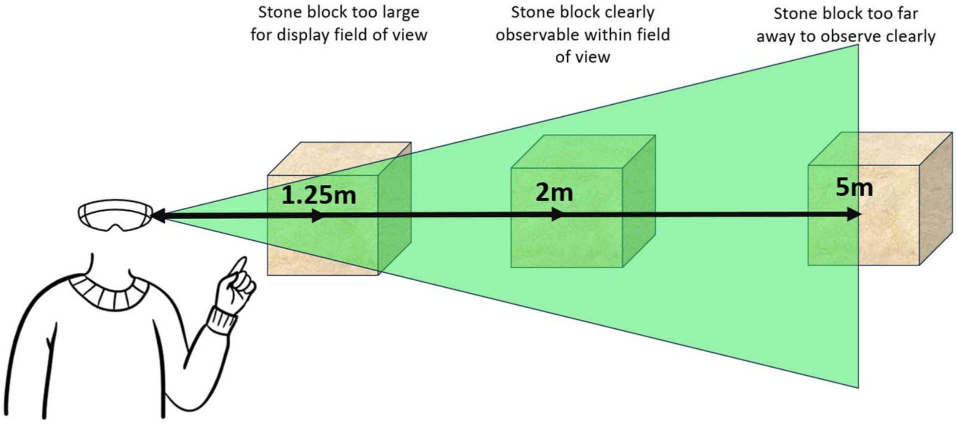


Figure 14: Optimal placement of holograms for HoloLens

Another potentially limiting factor of MR interaction is that of depth perception. It is known that in both purely virtual and mixed environments, users commonly underestimate depth [111], however, in a mixed environment this can be mitigated with the use of shadowing [112]. When interacting with items on a flat plane this can present itself as an issue, as the lack of depth information can cause the user to inadvertently move objects too far backwards/forwards.

The aspects of visual angle have been covered in previous work [113] to tackle neck and eye fatigue, however, the issue of fatigue of the arms also becomes prevalent over extended periods of operation. This is a crucial aspect for simulation-based education and training as the technology is required to purely assist training, and not cause additional problems that will not be found in the workplace. The nature of the HoloLens' limited field of view means that gestures must be performed within a strict "gesture frame", shown in Figure 15.

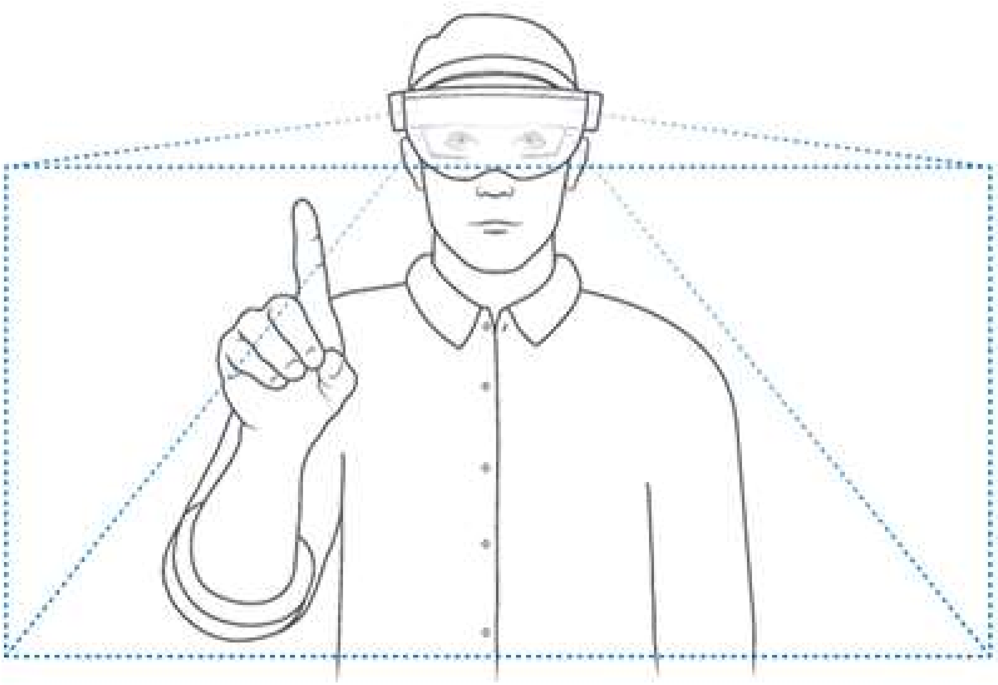


Figure 15: The gesture frame [Image credit: Microsoft]

Despite the field of view of the gesture frame being significantly larger than that of the device (120 x 120 degrees vs 17 x 20 degrees), it has been observed throughout the XR studies presented within this thesis that most users unprompted will attempt to perform all gesture related actions in their eyeline. This action often involves holding the arm out straight, which accelerates the onset of fatigue.

When observing whole arm movements, it is also important to consider ballistic movement [108]. This phenomenon is observed in this context when the arm moves very quickly to a point before making small adjustments. From this, a ratio can be calculated to find how much time proportionally is spent making these movements compared to the fine adjustments.

The final aim of any gain adjustment is to find the optimum balance between the stability of the application and the comfort of the user. Whilst it is tempting to focus solely on user comfort, some way needs to be given to the operation of the program itself, as a high degree of user comfort is no use if the application is now difficult to control in an accurate manner. A balance must be struck between intuition and the needs of the application. By default, a CD value of 2 is used in the operating system of the HoloLens.

2.6 Digital Twins

DTs facilitate collaborative working across people, infrastructure, distributed assets, and networks. Alongside AI and robotics, the aim of the DT is to enhance collaboration, corroboration, and cooperation in industrial environments. This subsection will present a categorisation of DTs, and a literature review of currently existing, planned and reviewed DTs in the offshore renewable energy sector. This is followed by a brief overview of the current issues faced by DTs and the proposed future direction.

2.6.1 Categorisation of Digital Twins

Currently, most digital twins are developed with unidirectional information flows. This means information flows from the DT to the user, but the DT cannot capture knowledge from the user [114], [115], [116]. Hence, these DTs cannot be considered symbiotic, as only the human can benefit in this knowledge exchange. DTs can be categorised into six stages, shown in Figure 16. Stages 1-3 cover existing DT methodologies. Stage 1 are status twins, which simply display the run-time status of a fixed number of assets. Stage 2 operational twins are scalable twins which store historical events. Stage 3 operational twins use ML with this past data set to predict future events. The end goal of the DT system is full autonomy, where the twin can self-improve automatically through learning from the past and the future and has the capability to make financial decisions. The DT contained within this work was developed as a Stage 4 DT with extended simulation and data analytic capabilities. This ensures positive interdependency across internal and external functions, which allows the integration of run-time sensor processing and data streaming with other inputs and services.

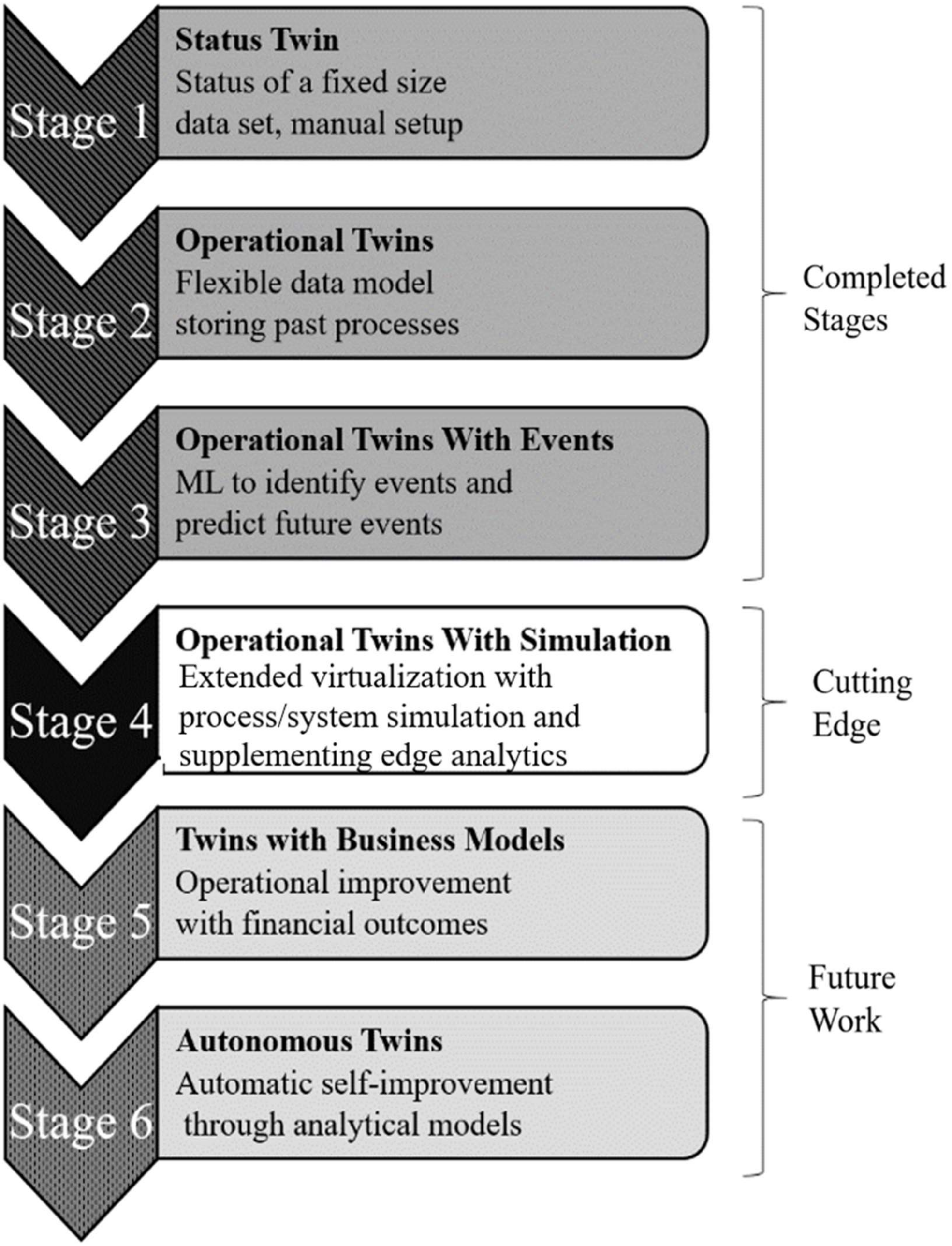


Figure 16: DT stages. Stage 4 is highlighted as the current digital twin model contained within this work.

Three main challenges for human-robot collaboration were cited by Hastie et al. [117]. These are:

- Planning in human-robot teams
- Executing and monitoring a task

- Adaptivity of the human robot partnership

Addressing these challenges requires pre-mission planning, situation monitoring with the option to manually intervene and re-synchronisation of the robot and the human on connection loss. Cloud robotics have become viable as internet connectivity and cloud services become more prevalent, with 92% of organisations having some cloud presence in their operations [118]. This enables extremely powerful compute platforms without the associated hardware, physical space, and servicing costs. These platforms also afford ease of integration with edge devices and robotics, enabling human-robot interfacing.

2.6.2 Existing Digital Twin Implementations in the Energy Sector

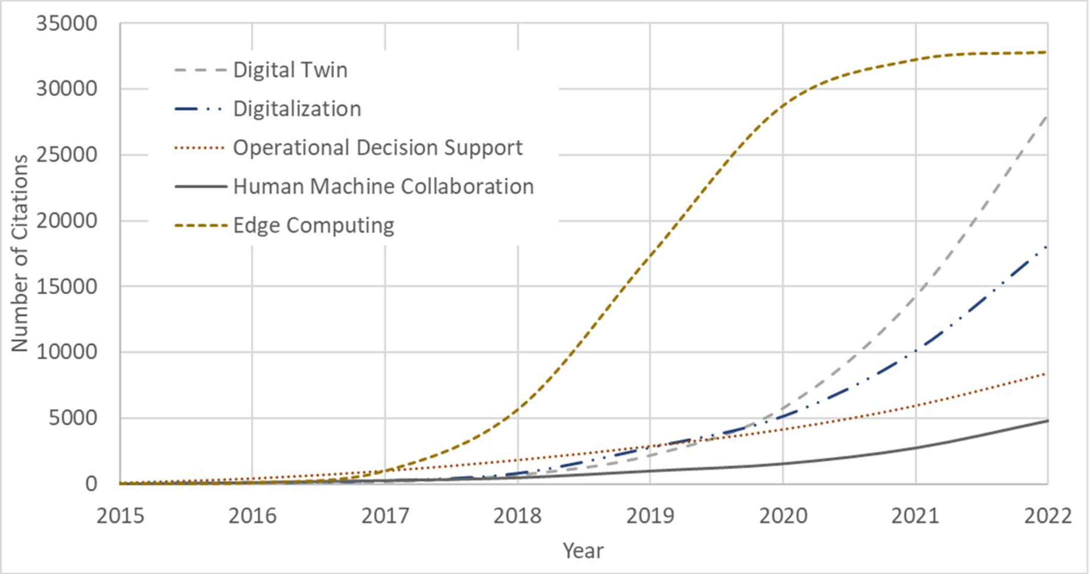


Figure 17: Variation of number of citations per year per keyword.

A search of academic abstracts, titles and keywords in Scopus was carried out between the years of 2015-2022. The keywords chosen were Digital Twin, Digitalization, Operational Decision Support, Human Machine Collaboration and Edge Computing. Figure 17 shows the number of citations per year per keyword, measured individually. The search revealed an increasing trend in digitalisation techniques since 2015. However, whilst there are many works on each individual aspect, the title, abstract and keyword search did not reveal any works which addressed all the areas searched, identifying a gap in the research. Some selected works and their features are shown in Table 5.

Table 5: Comparison of selected papers from Scopus keyword search

Ref	Digital Twin	Digitalization	Operational Decision Support	Human Machine Collaboration	Edge Computing
Onggo [119]	░	▓	░	▓	▓
Rauscher [120]	░	░	░	▓	▓
Ritto [121]	░	░	▓	▓	▓
Schenk [122]	░	▓	░	▓	▓
Bellavista [123]	░	░	░	▓	░
Anton [124]	░	░	░	▓	░
Grandi [125]	░	▓	▓	░	▓
Elayan [126]	░	▓	░	▓	▓
Mostafa [127]	░	░	░	▓	▓
Tu [128]	░	▓	▓	░	░
He [129]	░	▓	░	░	░
Sun [130]	░	▓	▓	░	░
Schroeder [131]	░	▓	▓	▓	▓
Choi [132]	░	▓	▓	░	▓
Presented Work	░	░	░	░	░

Key:		
	░	Implemented
	▓	Not implemented

To clarify this gap in the context of offshore renewable energy, a Scopus search was performed to search abstracts and titles of journal and conference articles containing the phrases “Digital Twin” and “Offshore Energy”. 38 results were found excluding conference reviews and unavailable articles. These are compared in Table 6. The general trend observed is that most articles contain material pertaining to DT and operational decision support, and are missing the other search terms, both as an exact match and contextually. It was observed that while there were many instances of DTs, most were one way from the machine to the human and lacking in two-way human machine collaboration, which is discussed in this thesis. The lack of digitalisation work points to systems being built ground-up for DT rather than adapting existing technologies for use in DTs. Similarly, the results for edge computing indicates the reliance on either embedded sensors in equipment or heavy computation for DTs.

Of the highlighted works, Kong et al. (2020) was the only work to address all areas and includes some of the work found within the DT implementations in this thesis [8]. The work presented by Pairet et al. (2019) was a direct precursor to the direction taken for the resilience demonstration highlighted in Section 6: Implementation of CyPhER in Digital Twin Applications. This analysis represents a gap in the current knowledge for a DT that accounts for digitalisation, operational decision support, human-machine collaboration, and edge computing in the offshore renewable energy sector.

Table 6: **Results of literature search and comparison of existing and proposed DTs for the offshore renewable energy sector.**

Ref	Offshore Renewable Energy	Digital Twin	Digitalization	Operational Decision Support	Human Machine Collaboration	Edge Computing
Li [133]	░	▓	▓	▓	▓	▓
Li [134]	░	░	▓	░	▓	░
Feng [135]	░	░	▓	▓	▓	▓
Pawar [136]	░	░	▓	░	▓	▓
Augustyn [137]	░	░	▓	░	▓	▓
Sahal [138]	▓	░	░	░	▓	░
Wang [139]	▓	░	░	░	▓	▓
Cai [140]	▓	░	▓	▓	▓	▓
Seo [141]	░	░	▓	▓	▓	▓
Coupry [142]	▓	░	▓	░	▓	░
Delgado [19]	░	░	▓	░	▓	░
Wang [143]	░	░	▓	░	░	░
Leng [144]	▓	░	▓	▓	▓	▓
Wen-hao [145]	░	░	▓	░	▓	▓
Seo [146]	░	▓	▓	▓	▓	▓
Sahal [147]	▓	░	▓	░	▓	░
Xie [148]	▓	░	▓	▓	▓	▓
Ayerbe [149]	▓	░	░	░	▓	▓
Martelli [150]	░	░	░	░	▓	▓
Wanasinghe [151]	▓	░	░	░	░	░
Malekloo [152]	░	░	▓	░	▓	░
Nielsen [153]	░	░	▓	░	▓	▓
Liu [154]	▓	░	▓	░	▓	▓
Liu [155]	▓	░	▓	░	░	░
Kong [8]	░	░	░	░	░	░
Zheng [156]	▓	░	▓	░	▓	▓
Wagg [157]	▓	░	▓	░	▓	▓
Lu [158]	▓	░	▓	▓	▓	▓
Zhou [159]	░	░	▓	▓	▓	▓
Etxegarai [160]	░	░	▓	▓	▓	▓
Zeitouni [161]	▓	░	▓	▓	▓	▓
Ngo [162]	▓	░	▓	▓	▓	▓
Boje [163]	▓	░	▓	░	░	▓
Ghita [164]	▓	░	░	▓	▓	▓
Gardner [165]	▓	░	▓	░	▓	▓
Okita [166]	▓	░	▓	░	▓	▓
Laamarti [167]	▓	░	▓	░	▓	░
Pairet [168]	░	░	░	░	░	▓
Presented Work	░	░	░	░	░	░

Key:
░ Implemented
▓ Not implemented

2.6.3 Problems Faced by Current Twins

One challenge faced by current twins is the lack of standardisation across systems. DT solutions currently on the market are bespoke systems made for specific sets of equipment or enterprises. There are no existing, observed, global standards for data formats, data transmission or connectivity concerning DTs. This brings around challenges for interoperability – closed and separate systems cannot interact in a symbiotic manner. This poses yet further challenges with respect to digitalisation, automation, and integration, which stunts the development of DT technology and methodologies.

Challenges exist with marrying large numbers of assets with the processing power required to monitor the assets. There are solutions which exist which are capable of processing data from a large number of assets, but require centralised data processing systems to do so [169], [170], [171], [172]. Conversely, solutions that use low powered hardware are limited in the number of assets they can monitor [173], [174]. Therefore, the flexibility and scalability of hardware for monitoring assets and processing data is a major challenge currently facing DT implementations.

2.7 Summary

This literature review has provided the following comparisons:

- Contemporary extended reality technologies.
- Contemporary digital learning research.
- Established and proposed digital twins in the offshore energy sector.

In addition, it has evaluated gaps in the existing research in each area addressed within this thesis. Identifying these gaps affirms the novelty of CyPhER. The gaps are current limitations in the development of human-systems interactions. Some demonstrate a lack of implementation, while others are identified from the lack of answers to some questions proposed in the literature. These were identified as follows:

- Multi-purpose digital thread frameworks for cyber-physical twinning which provide an extended reality.
- Symbiotic digital twins, which address the areas of digitalisation, operational decision support, human machine collaboration and edge computing. While not explicitly

mentioned in literature, the trends highlighted in previous research point to the need for such twins.

- Proposed and implemented digital twins for the offshore renewable energy sector which address the above areas.
- Interoperable, standardised digital twins which are application, platform and data agnostic.
- Safe vocational education and training techniques which afford the student with the use of real tools.
- The use of extended reality tools in vocational education and training.
- Control-Display gains for extended reality.

These gaps are all challenges to achieving a data and application agnostic cyber-physical twinning framework. Addressing these areas will provide some progress on the route to human-systems symbiosis. This also lends CyPhER industry relevance, as it addresses each of these areas it provides a framework for multimodal applications. Table 7 specifies what challenges CyPhER contributes towards.

Table 7: CyPhER's contribution to identified challenges.

Challenges	**Contribution**
Extended Reality	✓
Digital Twins	✓
Interoperation with Hardware and Software	✓
Mixed Reality Vocational Education	✓
Human-System Symbiosis	✓
Control-Display Gains	✓
Business Management	X
Application Development Kit	X
Industry 4.0	X
Robotic Platform Development	X
Pedagogical Studies	X
Data Security	X

3 Methodology and Implementation

This chapter will cover the methodology used in this study. First it will briefly explain the rationale for the CyPhER framework, before proposing the reference architecture, introducing the case studies and the verification, testing and validation methods.

The methodology aimed to answer the hypothesis proposed: "Human-system symbiosis can be enhanced by extended reality through a generalised digital thread framework that facilitates cyber-physical twinning." To achieve this, case studies were developed to address the research gaps identified within the literature review (see Section 2.7 Summary). The success of CyPhER was evaluated using quantitative survey data from case study experiments, and quantitative human and system performance metrics. These data were analysed with statistical tests where appropriate. The focus on quantitative data is due to the identified gaps CyPhER aims to fill – as there is no scope to tackle challenges in fields such as business management no qualitative assessment was required.

3.1 Design

CyPhER is designed to enable any device or system to form part of a cyber-physical twin, which is the integration of a cyber-physical system and a digital twin. Figure 18 demonstrates the foundational conceptual interactions of CyPhER to achieve symbiosis. This is attained through an action/feedback loop which informs the interactor (human or machine) of their impact of the system, allowing them to make more informed decisions on how to perform further actions within the system. This fundamental concept is the approach used for the case studies found within this work. The aim of the development of this concept is extending reality through symbiotic interactions between a human and a system. Additionally, accounting for machine-system interactions enable symbiotic machine behaviour within a system.

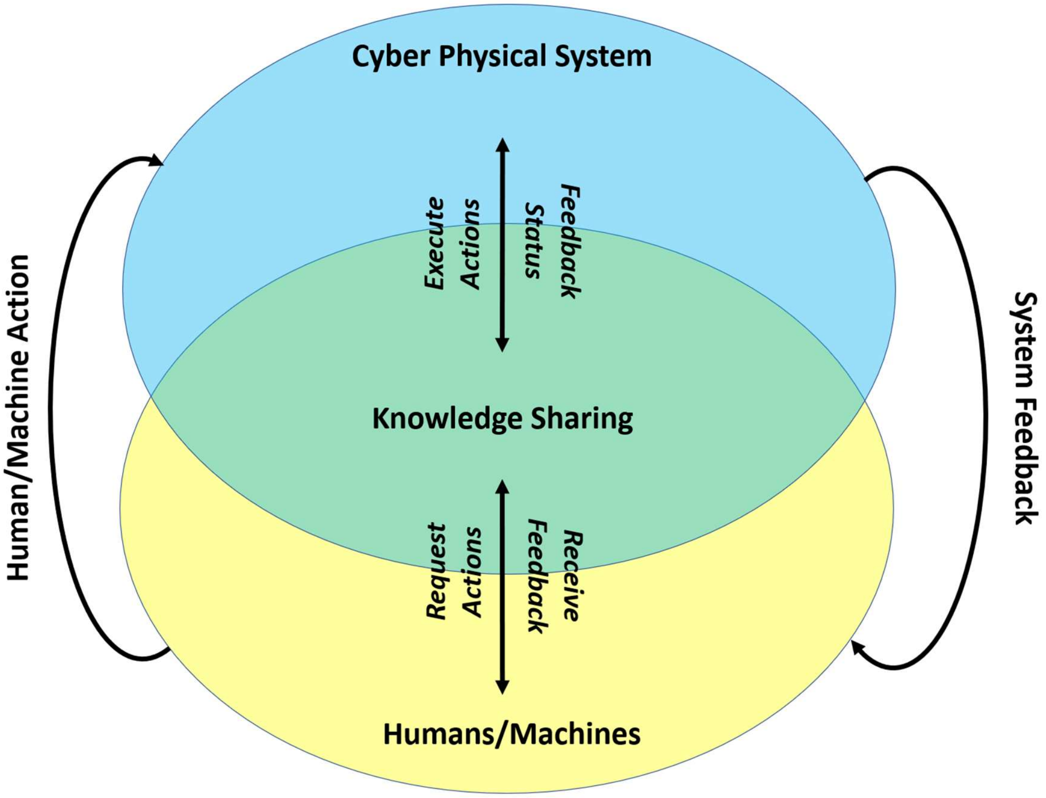


Figure 18: Symbiotic approach of CyPhER

Relevant technologies have now advanced to a stage where they can be used in industry and education, however most current solutions are constructed around the presence of immobile, powerful hardware, especially in industry scenarios. In creating a framework considering low computational and network bandwidth costs, the use of more portable and remote hardware can be introduced. Additionally, CyPhER is designed to be input, data and application agnostic while serving as a base for standardising data transactions. Features such as control display gains are utilised to enhance human-system interaction. CyPhER attempts to address gaps in existing work by being a multi-purpose digital thread framework for cyber-physical twinning and providing an extended reality. It is grounded on cyber-physical systems and is designed to provide a base to enable future developers to create cyber-physical twin solutions. CyPhER does not address issues such as out-of-sync data, custom input methodologies or application development directly – the importance of these elements differs depending on the field in which CyPhER is deployed and often requires bespoke development for each application. It is for these reasons these issues are not covered in this work.

CyPhER contains the following essential features:

- Device and platform agnostic
- Low computational resource use
- Synchronous multimodal data communication
- Compatible with low bandwidth
- Enable bidirectional information exchange
- Plug-and-use functionality for CPS
- Provide human- and machine-system symbiosis

Additionally, CyPhER can accommodate the following desirable features:

- Command and control for beyond visual line-of-sight
- Extended reality
- Remote monitoring

3.2 Cyber Physical Twin

Implementing a cyber-physical twin methodology in CyPhER allows for the digital (cyber) twin to be influenced by external conditions detected and signalled by the physical twin. A basic architecture of a cyber-physical twin is shown in Figure 19.

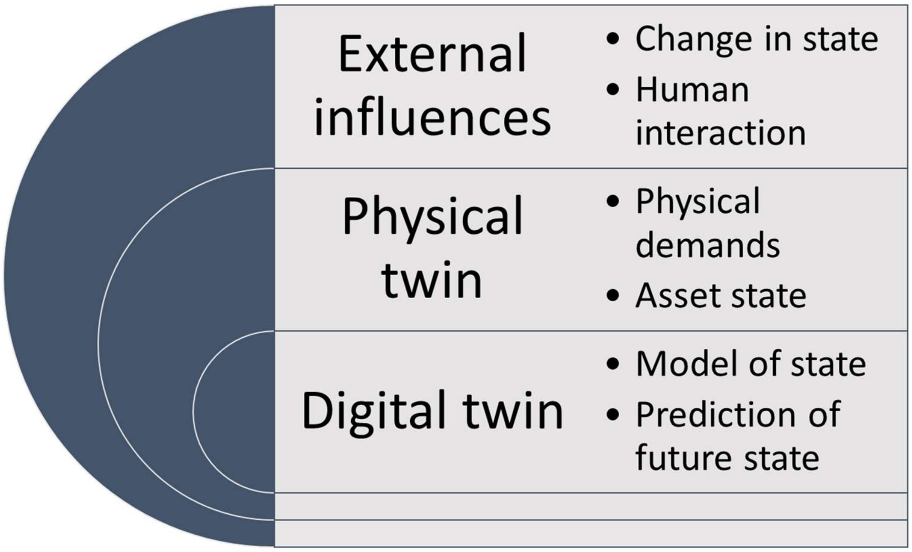


Figure 19: Overview of a cyber-physical twin architecture [figure adapted from Czwick et al. [15]].

Using twins in this way enables a bi-directional DT. The DT can give knowledge to the user through the current and future state of a physical asset using feedback from the asset. This also enables the human to give knowledge to the asset – through simulation of a process, the human can review the best course of action and feed this information through the user interface to the cyber-physical twin. Thus, a symbiotic relationship is formed between the human and the system.

3.3 Implementation

CyPhER allows a human to interact with a cyber-physical twin system, using any device, input method or communication method available. It is not imperative that the system designer use CyPhER in this way – it has been designed to be flexible and certain parts of the framework can be used individually, swapped or removed.

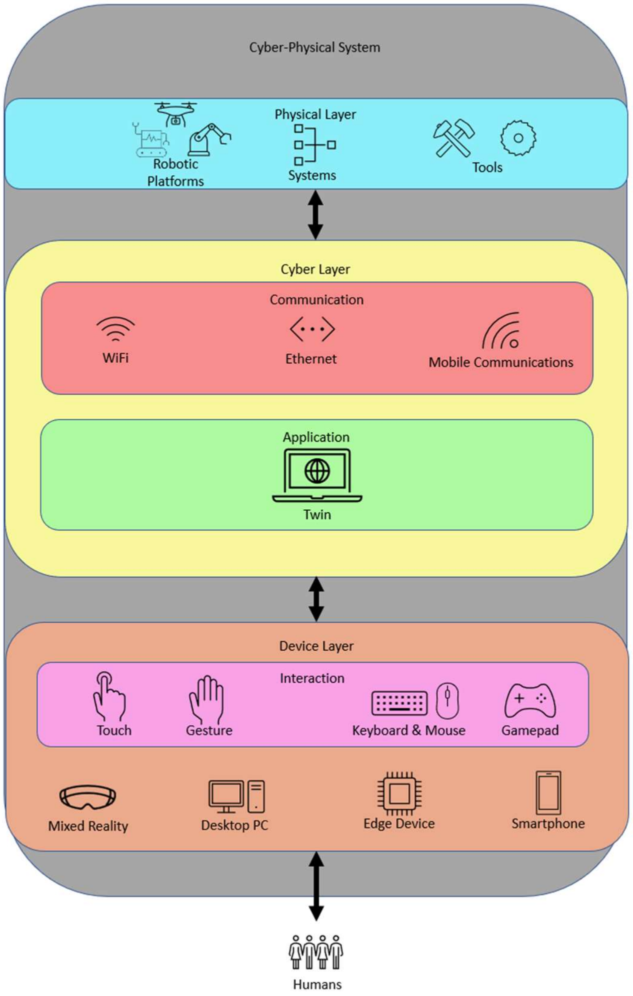


Figure 20: Cyber Physical Twin reference architecture.

Figure 20 shows the proposed reference architecture for this framework in terms of the specific practical implementations required, focussing on the different layers required to create the cyber-physical system. Each layer is described in Table 8.

Table 8: Description of reference architecture layers

Physical layer	The physical systems, platforms and tools, which are being controlled and monitored via bidirectional interaction with the cyber layer. Controlling can occur through physical manipulation or sending commands to autonomous systems. Monitoring can occur through onboard sensors or built-in system ontology.
Cyber layer	The communication methodologies and software applications which provide the interface between the device and the physical world. The communications can be performed using WiFi, ethernet, mobile network technologies or any other physical or wireless interface. Software applications are designed to the specific implementation of CyPhER. These can take the shape of DTs, games, simulation software, etc.
Device layer	Hardware which provides the interface between humans and the cyber layer. Interactions are provided depending on the device platform and implementation, and include touch and gesture controls, as well as traditional keyboard & mouse and gamepad inputs. Devices range in power, form and function dependent on implementation. Fundamental to XR operations are Control-Display gains, which are covered in further detail in section 4 Control-Display Gains.
Humans	Protocols for user interaction and device layer interface.

Current practical constraints with this implementation include needing to redesign the application based on the chosen input methodology – whilst it is possible for an application to compile and run on a multitude of platforms with minimal retooling using middleware such as Unity, there is currently no method of designing an application to consider all possible input modalities simultaneously. Therefore, the user interface will need adaptation for each modality. Furthermore, there is currently no implementation for a full web-based application e.g., cloud-based applications. All applications either rely on a local server host or peer-to-peer network communications.

3.3.1 Data Transmission Method

For data transmissions in the presented framework, the Transmission Control Protocol (TCP) transport layer is used opposed to User Datagram Protocol (UDP), due to the inherent error checking mechanisms and use in similar systems (such as ubiITS) [175]. Despite UDP being the faster method, for the purposes of CyPhER it is vital that the packets arrive intact and in the correct order, which TCP facilitates with inherent error checking allowing identification of dropped packets. The focus of the transmission of data for this framework is on reliability rather than ultimate performance, and for this purpose, TCP is the better protocol to use.

Table 9: Comparison of TCP and UDP protocols. Table modified from [176] and [177]

Property	**TCP**	**UDP**
Reliability	Higher	Lower
Ordering of Messages	Higher	Lower
Congestion Control	Higher	Lower
End-To-End Exchange Speed	Lower	Higher
Data throughput	Highere	Lower

Sockets are utilised to provide a connection between all hardware involved [178]. Using sockets allows a connection to be kept open whilst the application is running and provides an identifier for the connection, allowing for it to be called from within the program. This also allows for multiple devices to connect through multiple ports, which is essential for applications which involve numerous clients.

3.3.2 Threading

Multithreading can be found in almost all modern computing devices [179]. This allows a procedure to run on one processing thread whilst the rest of the application continues to operate on a separate thread, to prevent data processing and network latency stalling the application due to the socket approach used [180]. If data arrives late, then the method called to deal with that data will also execute late, and this causes the thread to become stalled. If all processes are carried out on the same thread, then this will cause the entire application to stall whilst it waits for the data to arrive and be processed.

3.3.3 Data Transfer Method

Two data transfer methods were used for this framework, depending on the application requirements.

Analytics transfer is handled using JSON (JavaScript Object Notation) files [181], to integrate with the Beaconing service the analytics were acquired for. JSON is unique as a lightweight data-interchange format that can be parsed easily by humans and machines alike. The format is language independent, and its nature as a standard text format means it can be opened and parsed in almost any script. JSON allows the transfer of objects, arrays, values, strings, and numbers over a network in very small files, as there is no overhead beyond the bytes each character uses.

Rapid transfer of information to and from a system, such as a robotic platform, are sent as strings. This enables more customisation over the size and contents of the message sent. If the data will always arrive in the same order, it is possible to reduce the message size by trimming all unnecessary information on the sender side, and instead parsing the string on the receiver side with the knowledge of what each segment of the string means. If the order of the data is not known, it is still possible to parse the data on the receiver side by searching for key characters. In addition, using strings in this manner means sending commands to a client which has a selection of pre-determined actions can be done using an extremely small packet size, usually just a single character. This helps CyPhER operate in bandwidth constrained scenarios, like those often found in challenging environments such as offshore wind farms. Examples of this are shown in Figure 21.

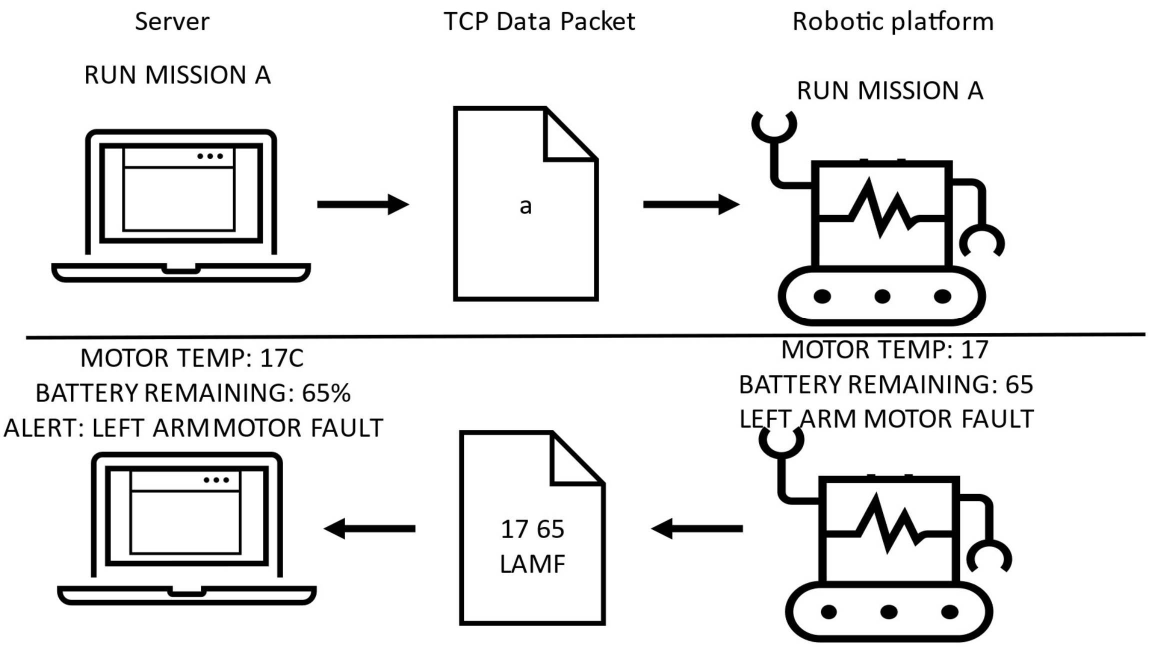


Figure 21: Examples of runtime TCP packet communication between a server and a robotic platform.

3.3.4 Ensuring Device Agnosticism

Device agnosticism is critical for ensuring interoperability in a system. While it is impossible to be completely device agnostic when considering very early computing technology or future technology which may not be backwards compatible with the techniques of today, it is important to ensure that CyPhER will work on as many systems as possible. TCP sockets are available as a built-in feature in most major programming languages, including Python, C++ and C#. The wide support of compilers for these languages means it is possible to use this method across many operating systems, including Linux-based platforms such as Ubuntu, Apple Silicon/Intel/PowerPC based Macs, Windows, Android and iOS.

Specifically for the HoloLens, the main challenge encountered during this development stage was major API differences between a desktop .NET standard and the different namespaces available for usage on Universal Windows Platform (UWP) applications. This was been combined with deprecated support for the .NET backend in Unity3D [182], which uses a limited subset of standard .NET 4.5 and allows the use of the Windows namespace for UWP, instead moving towards IL2CPP [183], which is a proprietary scripting backend for Unity3D. The flow for this backend is shown below in Figure 22.

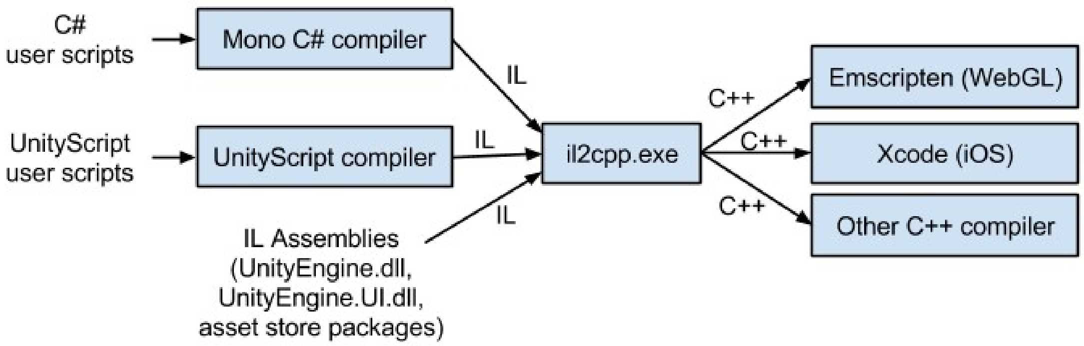


Figure 22: IL2CPP flow

IL2CPP takes the output from the compiled user scripts (in this case C# user scripts), then runs them through the IL2CPP Ahead-Of-Time (AOT) compiler il2cpp.exe. From this, C++ code is generated which is passed through to a platform specific C++ compiler ("Other C++ compiler" in Figure 22).

The advantage of using this backend, aside from continuing support, is that it is possible to use desktop .NET 4.x features such as manual threading and networking sockets in UWP applications. However, this comes with the cost of increased backing storage usage (builds can be up to 2x larger) and substantially longer build times during application revisions, as well as being closed source.

Also critical to extended reality operations within a HoloLens are control-display gains. These govern all gesture-based interactions within the mixed reality space. Achieving a desirable CD gain allows for more intuitive navigation and handling of virtual objects. CD gains are fundamental to human-computer interaction with graphical interfaces and so must be considered in an extended reality context.

3.4 Evaluation

The verification of the effectiveness of CyPhER has been performed through comparing the capabilities of the framework to the fields identified in literature. The case studies for MRVET and for symbiotic DTs demonstrate two diverse fields involving cyber-physical twinning, and the success of the studies are evaluated through user feedback and application capability. These case studies introduced novelties in their fields and developed CyPhER, as well as validating it in their use. To obtain the necessary performance data, a test application which uses all the essential features of CyPhER was used. This test application is described in Section 6.6 Fan Control Test Application. Data collected included the following:

- Latency
- Thread usage
- Memory usage
- Portability

From these factors, it is possible to numerically gauge the performance and capability of CyPhER. Numerical performance analyses are available in 8.4 CyPhER Numerical Metrics.

3.5 Summary

The approach taken within this work aims to tackle the identified limitations within current DT and CPS approaches. The digital thread enables information to be linked and transferred between the physical and cyber spaces through cyber physical twins. CyPhER is constructed to resolve challenges in achieving human-systems symbiosis, which can be found in user interaction and interfacing, DT design and implementation. Interoperability is taken into account with regards to the DT, opening up avenues for DT deployment on diverse hardware platforms for a variety of applications.

To prove out the viability of CyPhER, two industry-led case studies were completed. The first involves a virtual learning environment, the second involves digital twins of industrial robots. These were chosen to show the flexibility of CyPhER in achieving application and platform agnosticism and achieving data transfer requirements in various environmental settings.

4 Control-Display Gains

XR interactions are aimed at enriching the virtual-real interface to better execute appropriate actions, however, as stated in the literature review, work remains in determining how these interactions are performed. CD gains are the proportion (gain) between movements in the physical world to movements in the virtual world [108]. This chapter covers the development and testing of the investigation into the effects of CD gain in MR environments which, as highlighted in the literature review, had not been previously studied, and is a critical aspect of any human-computer interaction involving placing or moving digital items, shown by the ubiquity of pointer acceleration techniques on desktop systems. Addressing this will inform how to approach the human factors side of cyber physical interactions in CyPhER. Firstly, the method of testing is presented, covering the participants, apparatus used, testing application developed and practical testing measures. The results are then plotted and discussed.

4.1 Design of Experiment

The aim of the experiment is to determine what effect changing the CD gain has on user control in an MR environment. An intuitive CD gain allows for rapid, accurate operation of tools within a mixed reality environment, and enables an extended reality. This was done by measuring the precision and speed of virtual object placement in a repeatable test. To this end, two tests were devised, and then evaluated before one test was used to gather results. The aim of the experiment is to determine what effect changing the CD gain has on user control in an MR environment. This was done by measuring the precision and speed of virtual object placement in a repeatable test.

12 participants (one with pre-existing MR experience) performed 6 trials, registering 72 trials in all. All were in the 22-25 age range, and all had normal or corrected-to-normal vision. All trials were conducted under Heriot-Watt University's ethics standards, and all participants were recruited on campus. Not considered were cultural limitations, which could include not using a hand to point. Likewise, disabilities and age were not recorded which can affect hand movements and ability to hold a steady position. Relevant to VET, the education level of participants was not recorded, and the age range is above that which early-course VET students will generally be.

4.1.1 Apparatus

This test required the use of a Microsoft HoloLens device [76], shown in Figure 23. This device was chosen as the core MR technology for this study due to the extensive working documentation and the maturity of the device when compared to a similar device such as a Magic Leap One.

Figure 23: Microsoft HoloLens [Image credit: Microsoft]

The environment was built in Visual C# on Unity 2018.2.8f1, using the MRTK from Microsoft [184], and streamed over a Wireless Local Area Network (WLAN) using the HoloLens' built in remoting function [185]. A basic flow overview is shown in Figure 24.

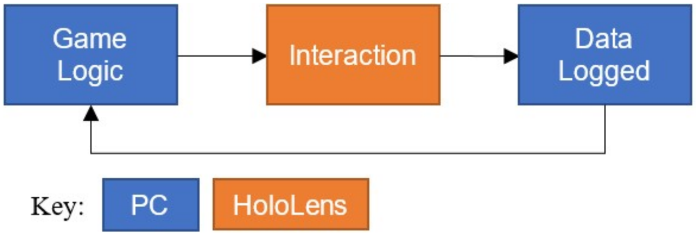


Figure 24: Application flow overview

The remoting was used to ensure the application's frame rate was constant, as it was found the frame rate of the application could fluctuate on the device and previous testing has indicated this affects the results obtained [113]. The specifications of the PC used for streaming are outlined in Table 1.

Table 10: Streaming/development PC specifications

CPU	Intel Core i7-2600 3.40GHz
RAM	16GB 1333MHz DDR3
GPU	2GB Nvidia Quadro 4000
Operating System	Windows 10 Enterprise

4.1.2 Testing Application

Participants were asked to play a game based on "Pipe Mania" [186] on the HoloLens. This used entirely gesture-based control and was placed at a virtual distance of 2m in front of the user. The basic aim of the game is to connect the bottom left corner of the game grid to the top right using a random array of pipes, completing the task before water overflows from a dead end. An example of the test environment is shown in Figure 25. The pipes were moved using the HoloLens' "Drag and Hold" gesture (Figure 12). The time limit set for the experiment was 20 minutes, restricted by the comfort of the headset.

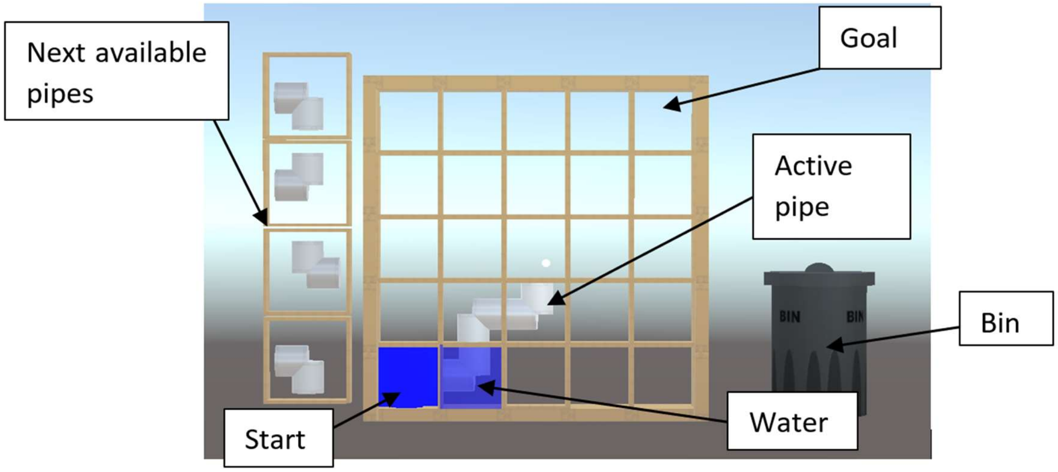


Figure 25: Example of the "Pipe Mania" test environment

The users' CD gain score was calculated from how accurately each pipe was placed in the square, and how long it took to drag the pipe to its place from its origin. The pipes were shaped to be an exact fit with the square and should line up exactly between squares. Accuracy of the pipes was calculated by the distance between the pipes' origin point and the centre of the grid square, when this is 0 the pieces line up to the square perfectly. The grid is flat on the z-axis (i.e., everything is at the same depth), however the movement of the pipes was not locked to any axis, to observe the effects of depth perception on the placement.

In keeping with the concepts of Pipe Mania, the pipes on the left-hand side of the screen were chosen from a selection of pre-made shapes at random, with a bias for pipes with an origin at the bottom of the square for the first placement. Users can pick from any of the available pipes, and if a user wants to generate a new pipe it is possible to "trash" pipes using the bin on the right-hand side of the screen. Binned parts were not recorded in this experiment. Water is shown by the squares becoming blue, once one square becomes solid blue the water will follow the trajectory of the pipes.

After a "Game Over" state is reached (success or failure), the CD gain was then altered, and the experiment restarted. Participants were taken through 8 different gain values and had one "test" run to familiarize themselves with the device and input methodology beforehand. Participants were not told of the change in gain. The environment was 2m away from the players, and they were asked to stand on the spot to keep this distance constant. The surrounding environment was a grey wall, to control any outside elements from interfering with the users' game. To acquire the data processed in the results, the movement of every piece interacted with, barring "trashed" parts, was logged in individual text files.

From this test, the following parameters were measured. These parameters were chosen for their ability to be measured programmatically and their relevance to human input:

- Time for placement of pipes. This measurement is fundamental for interactions, as it provides a reference for the perceived ease of moving an object and is critical for efficient usage of any graphical interface.
- Z-axis overshoot of placed pipes. This shows accidental overshoot on the depth axis, which was not used in the test. This demonstrates depth perception of pipe placement.
- X- and Y-axis overshoot of placed pipes. This measures how precisely an object can be placed rapidly.
- Number of adjustments made to placed objects. This shows how many attempts were needed on average per object to place it properly, which indicates how easy it was to place a pipe in the correct space.

- Ballistic movement ratio. This is the duration of rapid movements within the interaction time with each pipe and shows confidence in the manipulation of objects in a mixed reality space.

4.1.3 Measures

Prior to wearing the HoloLens, participants were shown how to wear the device, and were explained how the game works. Participants were given a few minutes to familiarise themselves with the interface and were allowed to attempt the game once prior to the commencement of the recorded portion of the test. If they began to feel uncomfortable, participants were given the opportunity to stop the test. The participant would play the game six times, with a different CD gain every time. The participants were not told the CD gain was changing, and the test environment was visually identical each time.

4.2 Results

Participants were tested at 6 CD Gains (0.5 - 3 in even increments of 0.5). The reasoning for this is to provide some variance around the default system CD Gain of 2. This allowed testing for values of less than one where the hand will move more than the object, 1:1 movement, and higher levels of acceleration. No personal information about the participants was taken.

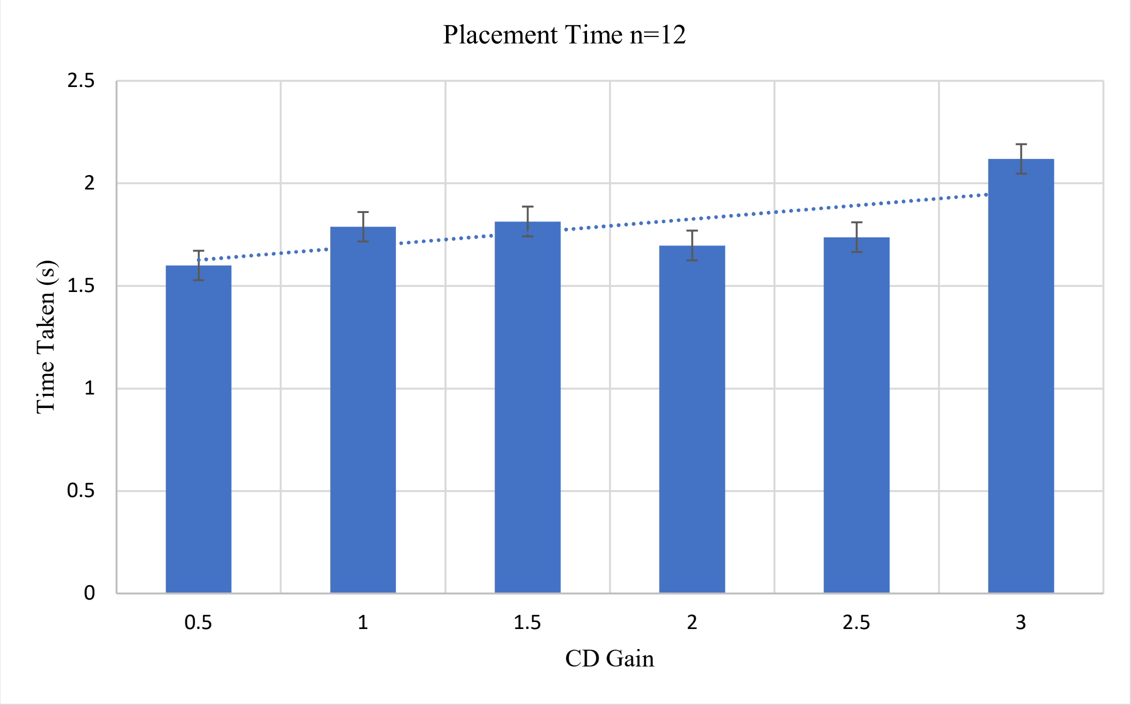


Figure 26: Average time for placement across all tested CD gains

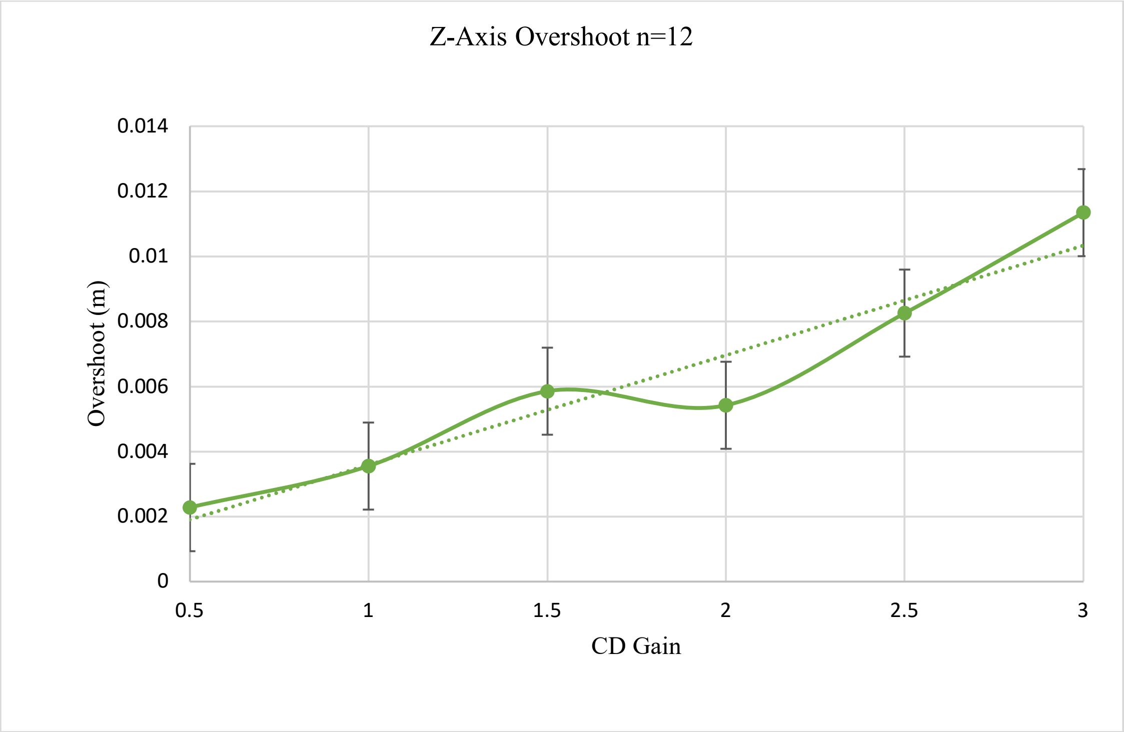


Figure 27: Average z-axis overshoot for placement across all tested CD gains

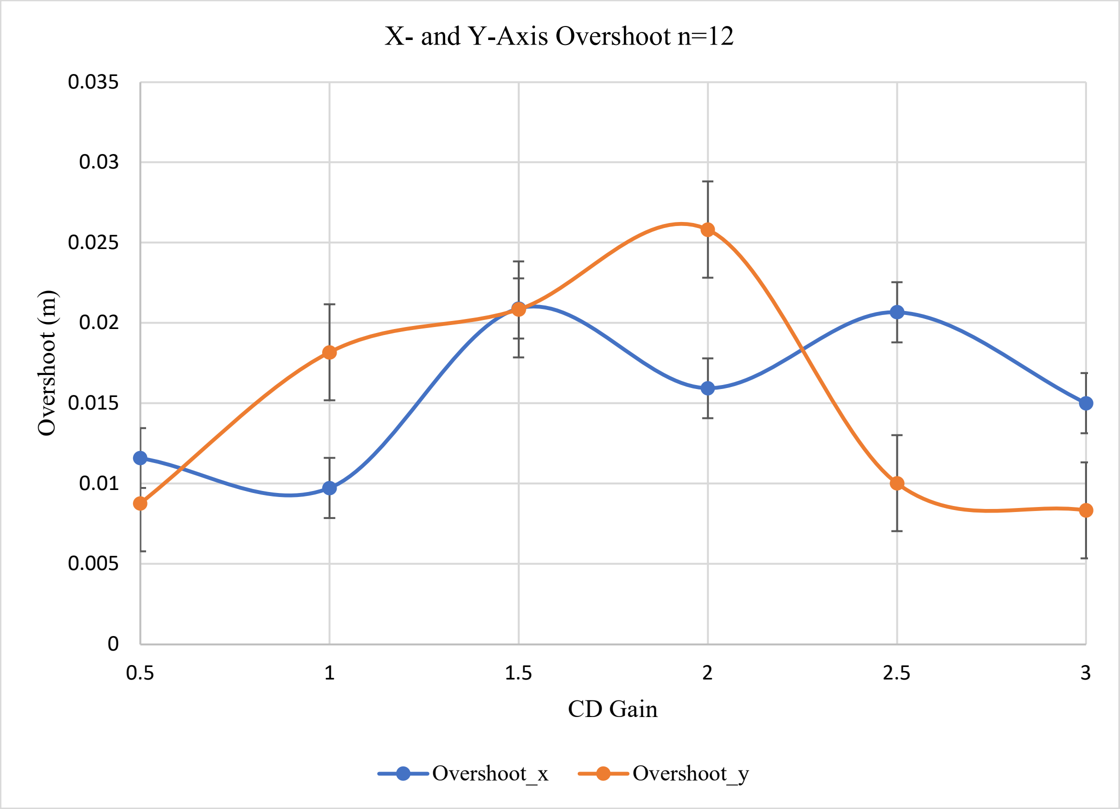


Figure 28: Observed overshoot on X and Y axes

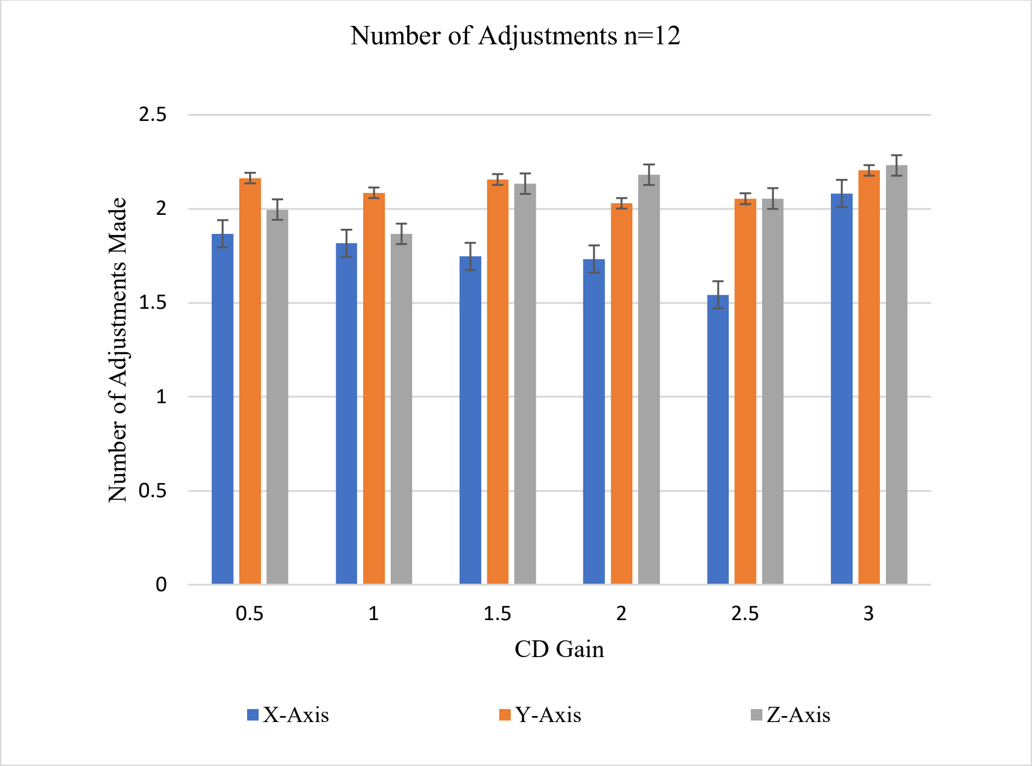


Figure 29: Number of adjustments made

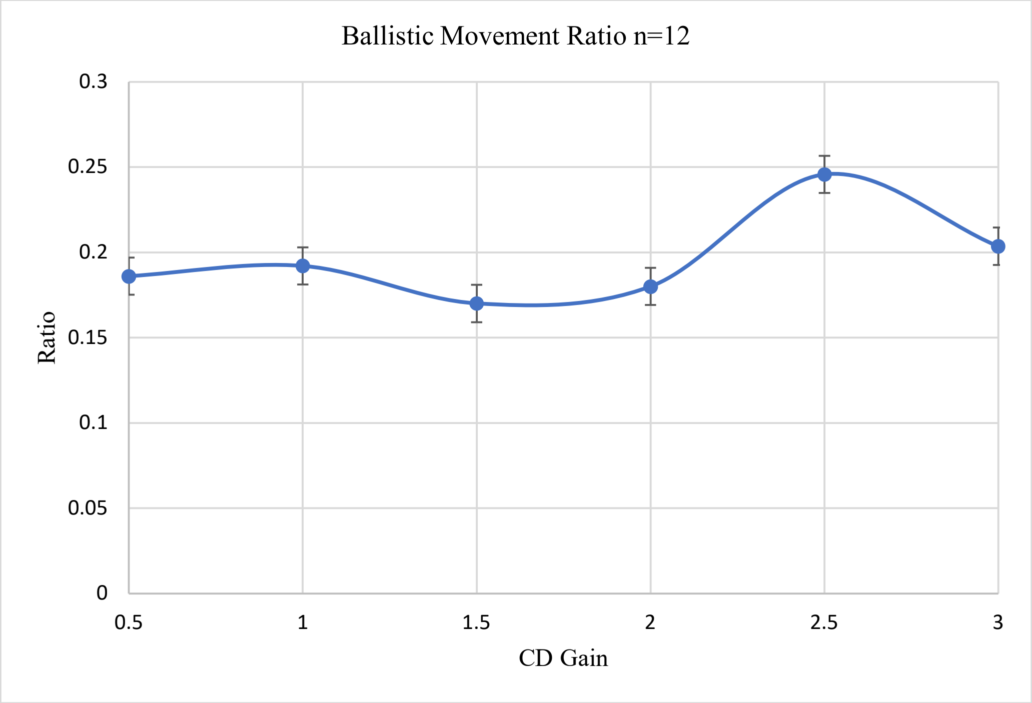


Figure 30: Ballistic movement ratios

4.3 Discussion of Results

The CD gain with the fastest time for placement was found to be 0.5. This is shown in Figure 26. Overall, a linear trend for time taken was observed as CD gain increased towards 3, however, the system default CD gain of 2 and a gain of 2.5 also observed reduced placement time. T-stat was found to be 11.92 ($p<0.05$), proving a statistically significant difference in results. The observed R squared level of 49.5% points to some variance in regression, but values <50% are to be expected when dealing with human behaviour. Optimal CD gain was expected to be 2 as this was the value observed from the previous test.

Figure 27 demonstrates the observed Z-axis overshoot (i.e., into the scene). A linear trend overall was observed, with the system default value of 2.0 outlying the other results observed. This trend was expected due to the increase in amplification of the user's movements, and the limited depth perception offered by the device. R squared was determined to be 92.5% for this data set, indicating a clear trend in the results and confirming the expected hypothesis.

Figure 28 demonstrates the overshoot observed on the X and Y axes. The trends are difficult to draw conclusions from. Whilst the lowest CD value produced the smallest overshoot (and hence the highest accuracy), the accuracy observed on the Y-Axis was at its worst at a CD gain of 2, before dramatically improving at higher values. There is also a large degree of error with these outlying values. A possible explanation is that the highest CD gains were tested last, and therefore the users had more experience with the nature of the controls at this point. Regardless, further testing is required with these gains to draw any reliable conclusion. Having a greater number of participants and trialling a wider range of CD values may prove useful in this regard. From the results obtained, there are likely not many usability gains to be found from varying the CD gain on the X and Y axes.

Figure 29 shows the number of adjustments made to placement. The expected impact is that the fewer adjustments made, the more comfortable user operation becomes. Generally, on the X- and Y-Axes, as gain increased fewer adjustments were made, this again points to the participants becoming more comfortable with the test as it goes on. On the Z-Axis, the opposite effect is observed, which indicates a lack of depth perception coming into play. A T-value of 19.58 ($p<0.05$) indicates error in the data, however a R squared value of 51.2% does indicate an upward trend in corrections as CD gain increased. Higher errors are also noted on specifically X-Axis placement with a CD gain of 3.0. The higher gain shows more adjustment, but it is important to observe that the placement of the object on the Z-Axis in this case is not critical to success of the puzzle. In general, it was observed that some parts in a row could be placed without correction, but if one part were not correctly placed at first, there would be several corrections to place it correctly.

Figure 30 shows the observed ballistic movement ratios. A linear trend was observed again, with the time spent carrying out ballistic movement increasing as the CD gain increased. This ranged from around 17% to around 25%. While the results have a high degree of change, with a t-value of 7.16 ($p<0.005$), an R squared value of 26.7% indicates there is at least some correlation here with a very rough trend towards an increase in ballistic movement as CD increased. The increase in ballistic movement found on the final two CD gain values can potentially be explained by the higher CD gain facilitating faster movement, and again by the participants becoming more comfortable with the virtual environment at this point. Generally, the more time spent in ballistic movement means there is less time spent making final adjustments. Comparing this with the observed Z-Axis movements shows that an attempted trade-off was made for time instead of accuracy, perhaps because of arm fatigue (the experiment had been running for 15+ minutes at this stage).

The observed trend in the results indicates that low CD values (0.5-2) give the best result in terms of placement time and accuracy. This is likely due to being able to perform larger movements of the arm while still maintaining precise placement. However, these results do not consider the factor of arm fatigue over an extended period. Whilst the placement times may be lower, the nature of using a CD of less than 1 means that the arms must move more than the object does, increasing exertion. Future work in this field would be analysing the effects of this fatigue over a prolonged period of time. Further work is also required in determining results for overshoot on the X and Y axes, as more participants are tested it is hoped that more clear results will be produced. Testing with more CD gains lower than 1 may also reveal some further insight into potential gains in user operability. More participants are also required to make a more solid determination on whether the trends observed on the Z-axis are truly linear or not. The implication from the results found is that the operating system default value of 2 produces the most reliable placements of objects in 3D space, but scope remains to see if varying acceleration with ballistic speed, as found in pointer acceleration in desktop systems, would produce usability gains. It would also be beneficial to perform this trial again with future hardware to determine if having 1:1 movement assists in object placement up close, but this does not tackle placement issues on distant objects, which this trial focussed on.

4.4 Summary

The study of CD gains indicates a balance must be struck between precise, short-term and longer-term operation, where arm fatigue comes into effect. This can be mitigated by a larger gesture frame, which would prevent the arms needing to be held in such an elevated position.

Another factor of interest since this study was carried out is the introduction of built-in, full hand tracking mechanisms on the HoloLens 2, which does allow for 1:1 manipulation of objects through a "grabbing" system. Considering this, it is possible to design a system where arms-length interaction is provided by grabbing, and only further afield interaction is performed using the gesture commands used in this study. This has been considered by Microsoft as the OS allows for these dual interaction types.

In conclusion, this is a critical area of further research to realise fully extended reality. Achieving an optimal CD gain allows the HoloLens to become an extension of reality, where operations accelerate human-machine symbiosis due to a more direct method of operating physical platforms and assets through a mixed virtual-physical space. The work produced here was critical to enabling the mixed reality interactions found within the next chapter, and the analytics collection was also used as groundwork for the analytics transfer within CyPhER.

5 Implementation of CyPhER in a Virtual Learning Environment

This chapter will focus on the implementation of the CyPhER framework in a virtual learning environment (VLE), developed as part of the EU Beaconing project (Grant #687676) [106]. The implementation focussed on the usage of XR for power tool training in further education institutions. The application was tested with students and tutors at City of Glasgow College, Edinburgh College, Forth Valley College and the Historic Scotland site in Elgin The application developed was based on a desktop version developed by Imaginary Games for the Beaconing project. Two platforms were developed for this application, one for PC and one for XR. These operate standalone but share learning outcomes. The PC version operated with a traditional mouse interface, whereas the XR version uses gesture-based controls. These controls were built using the knowledge attained in the prior CD gains research carried out. Both feature a 3D environment with tools to perform cutting operations on a virtual block of stone.

The study is to determine whether a CPS-based approach can extend the learning experience, and if so to what extent. This aims to address current issues in further education VET, which includes the inability for a student to practice using a powered stone cutter in their educational institutions, leading to accidents from inconsistent training in the construction workplace.

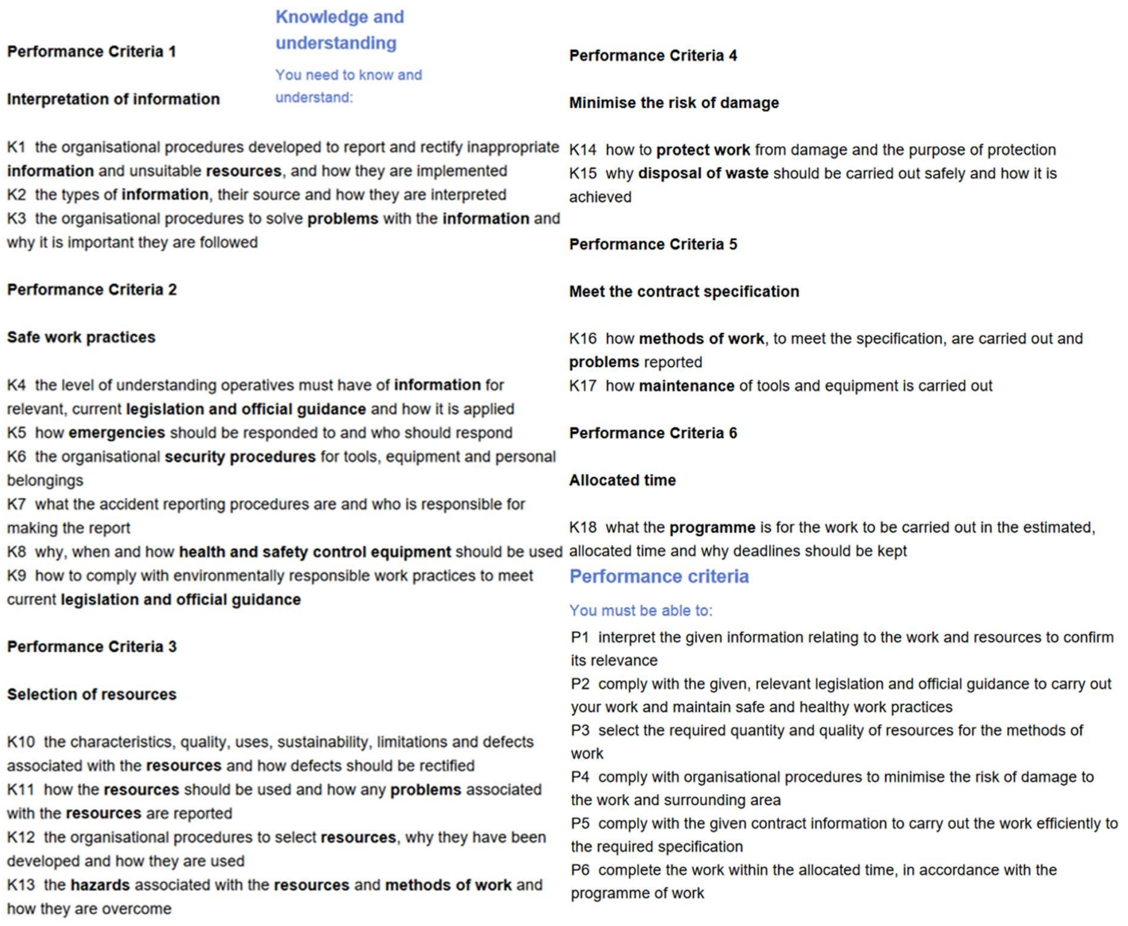
5.1 Application Domain

This application was developed for the Vocational Education and Training (VET) domain. The specific focus of the application is training the safe usage of a powered stone grinder. This requires the application to be mapped to a relevant standard, in this case COSVR195, “Produce standard architectural stone enrichments” [187]. This standard covers the production of standard architectural stone enrichments. This is the standard followed by the courses provided by the Scottish vocational education (VE) institutions which were contacted during the development process, City of Glasgow College, Forth Valley College and Edinburgh College.

For hardware, the Microsoft HoloLens was chosen. This hardware enabled the use of gesture and voice input, as well as the ability to track a real stone grinder through image-based tracking. Additionally, being a mixed reality device enabled the application to be used on the actual workshop floor, using the environment the students are familiar with and the environment most accurate to that in which these exercises are currently practically carried out.

5.2 Application Flow

As stated previously, the application is mapped to COSVR195. This standard is shown in Figure 31. The performance criteria ensures that a basic level of competence is met in training. Knowledge and understanding components develop the working attitudes. The application was developed to tackle as many of these aspects as possible.



Knowledge and understanding

You need to know and understand:

Performance Criteria 1

Interpretation of information

K1 the organisational procedures developed to report and rectify inappropriate **information** and unsuitable **resources**, and how they are implemented
K2 the types of **information**, their source and how they are interpreted
K3 the organisational procedures to solve **problems** with the **information** and why it is important they are followed

Performance Criteria 2

Safe work practices

K4 the level of understanding operatives must have of **information** for relevant, current **legislation and official guidance** and how it is applied
K5 how **emergencies** should be responded to and who should respond
K6 the organisational **security procedures** for tools, equipment and personal belongings
K7 what the accident reporting procedures are and who is responsible for making the report
K8 why, when and how **health and safety control equipment** should be used
K9 how to comply with environmentally responsible work practices to meet current **legislation and official guidance**

Performance Criteria 3

Selection of resources

K10 the characteristics, quality, uses, sustainability, limitations and defects associated with the **resources** and how defects should be rectified
K11 how the **resources** should be used and how any **problems** associated with the **resources** are reported
K12 the organisational procedures to select **resources**, why they have been developed and how they are used
K13 the **hazards** associated with the **resources** and **methods of work** and how they are overcome

Performance Criteria 4

Minimise the risk of damage

K14 how to **protect work** from damage and the purpose of protection
K15 why **disposal of waste** should be carried out safely and how it is achieved

Performance Criteria 5

Meet the contract specification

K16 how **methods of work**, to meet the specification, are carried out and **problems** reported
K17 how **maintenance** of tools and equipment is carried out

Performance Criteria 6

Allocated time

K18 what the **programme** is for the work to be carried out in the estimated, allocated time and why deadlines should be kept

Performance criteria

You must be able to:

P1 interpret the given information relating to the work and resources to confirm its relevance
P2 comply with the given, relevant legislation and official guidance to carry out your work and maintain safe and healthy work practices
P3 select the required quantity and quality of resources for the methods of work
P4 comply with organisational procedures to minimise the risk of damage to the work and surrounding area
P5 comply with the given contract information to carry out the work efficiently to the required specification
P6 complete the work within the allocated time, in accordance with the programme of work

Figure 31: COSVR195 Standard [187]

Within COSVR195, it is necessary for a student to be able to carry out the following tasks which are represented within the application:

1. Interpret drawings, specifications, schedules, method statements, risk assessments and manufacturers' information related to the work to be carried out.
2. Avoidance of risk by complying with given information.
3. Selection of resources.
4. Maintain a clear and tidy workspace.

5. Measure, mark out, shape and finish.
6. Use hand and power tools.

The mapping is demonstrated in Table 11. Mapping the application to an occupational standard ensures the usefulness of the pedagogical aspect of VET.

Table 11: Mapping to occupational standards

Participants	Location(s)	Resources	Evidence	Rewards
Students	Anywhere	Mixed Reality, CPS	COSVR195 P1-P6, K1-K16	Experience with an angle grinder, increased employability

The application flow shown in Figure 32 covers these points. The justification for the development of a MR version of this application was primarily to provide a training application which was more intuitive and immersive than the PC based training provided. In Scottish vocational education institutions, there is currently no provision for training with a real angle grinder. The usage of a real angle grinder in the MR application allows the students to gain some experience in a controlled environment before using the power tool in industry. This also contributes to an extended reality using the cyber-physical twin, with the physical twin of the blade contributing to the digital twin of the real-life stonecutting environment.

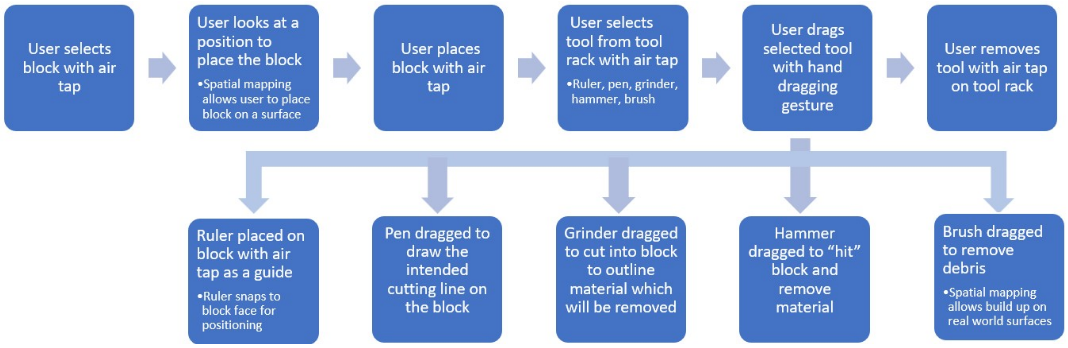


Figure 32: Application flow for VET application [6]

This flow covers all the basics of a typical stonemasonry procedure as described by COSVR195.

5.3 Application Development

In this application, CyPhER was utilised to enable the use of the HoloLens, and to provide the communications between the application and the VLE. The HoloLens was chosen as it was, at the time, the only available MR device, which enabled the real tool and environment interaction which was desired. Additionally, since it requires no extra hardware to operate it increases the ability to use it in a workshop environment. The application was developed in Unity3D and targeted UWP for HoloLens. Unity was chosen for its ability to deploy 32-bit UWP applications, extensive documentation, existing framework for 3D applications and support for both HoloLens and Vuforia image-based tracking. Microsoft's Mixed Reality Toolkit [188] was used to enable gesture-based actions. The specifications of the development PC are shown in Table 12.

Table 12: VET application development PC

PC Model	HP Compaq 8200 Elite CMT
CPU	Intel i7-2600 @ 3.4GHz
GPU	Nvidia Quadro 4000 2GB
RAM	16GB DDR3
Operating System	Windows 10 with Fall Creators Update, 64-bit
Development Environment	Unity 2017.3.1p1 (C#) [189] Microsoft Visual Studio 2017 [190]
Libraries Used	Mixed Reality Toolkit (Microsoft) [188] Vuforia (PTC) [191] .NET Sockets [178] .NET Threading [192]

The development environment was Unity 2017.3.1p1 using C#, with the Mixed Reality Toolkit provided by Microsoft enabling HoloLens specific interactions. Vuforia enabled the image-based tracking used for the stone grinder. The application was built on the development PC and deployed to the HoloLens over a WLAN connection.

5.4 Application Description

The application is designed to replicate the process of a real-life stonecutting operation. This is achieved using a real stone grinder on a virtual block or stone. This enables a training experience that cannot be obtained through purely practical or purely virtual means. The application ensures users are aware of the correct PPE required, the correct marking out and cutting techniques, and waste removal.

The application uses two control methods on the HoloLens depending on the tool selected. Tools which require constant movement interactions use the drag and hold input method, whereas tools which are placed and then need to be held still are located using the tap to place input method. These virtual tools were controlled with a CD gain of 2, using the results obtained from Section 4 Control-Display Gains.

For reference, a screenshot of the Imaginary Games desktop application and a photo of the real process are included at each applicable stage.

5.4.1 PPE Selection

The first stage of the application is to select the PPE required for a safe cut operation. The MR interface is shown in Figure 33, and the desktop interface in Figure 34. Skipping this step still allows the user to perform the cut, but it is logged that the PPE was not selected, which is highlighted on the VLE. Additionally, not selecting the mask results in the lung damage indicator becoming red as a cut is performed, causing a warning message to display when the lungs are at critical health to emphasise the importance of this piece of PPE.

Figure 33: PPE Selection interface [6].

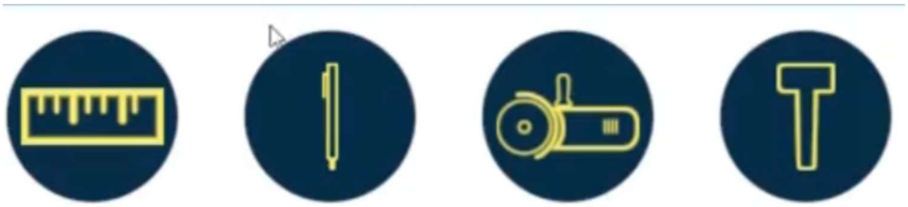


Figure 34: PC App PPE selection interface.

5.4.2 Tool Selection

The tool interface contains all the virtual tools required for the operation, ruler, marker, and hammer, shown in Figure 35. This interface is placed in world space. Selecting a tool will make the tool appear in 3D space in front of the block. The "playback" toggle is used to display the on-device replay of the cutting process carried out.

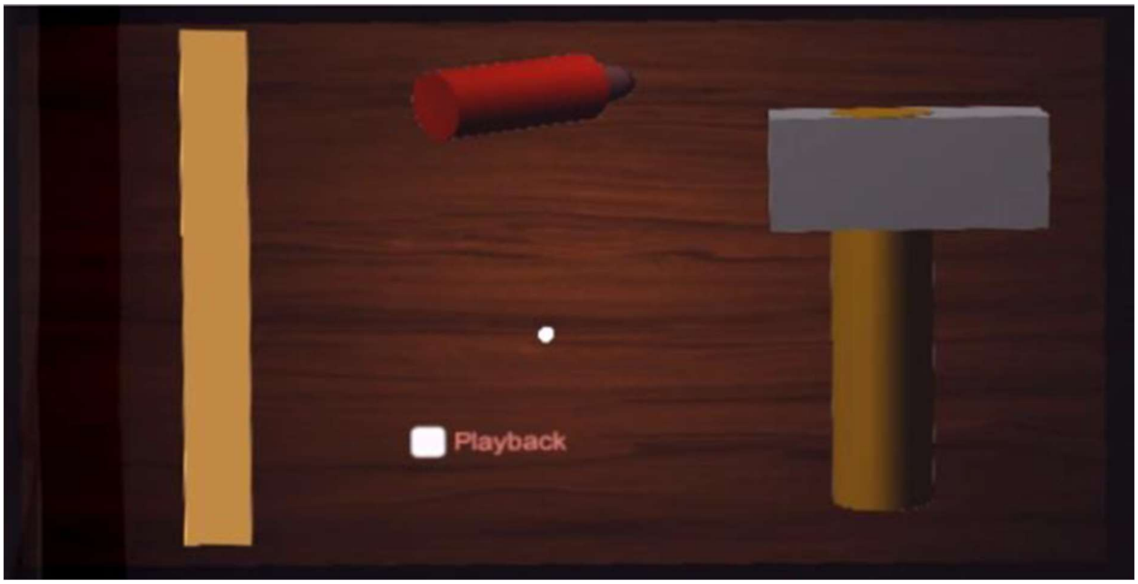


Figure 35: Tool selection interface [6].

5.4.3 Mission Display

The mission display, shown in Figure 36, is a 1:1 representation of the stone block with data representing the dimensions and shape of the cut required.

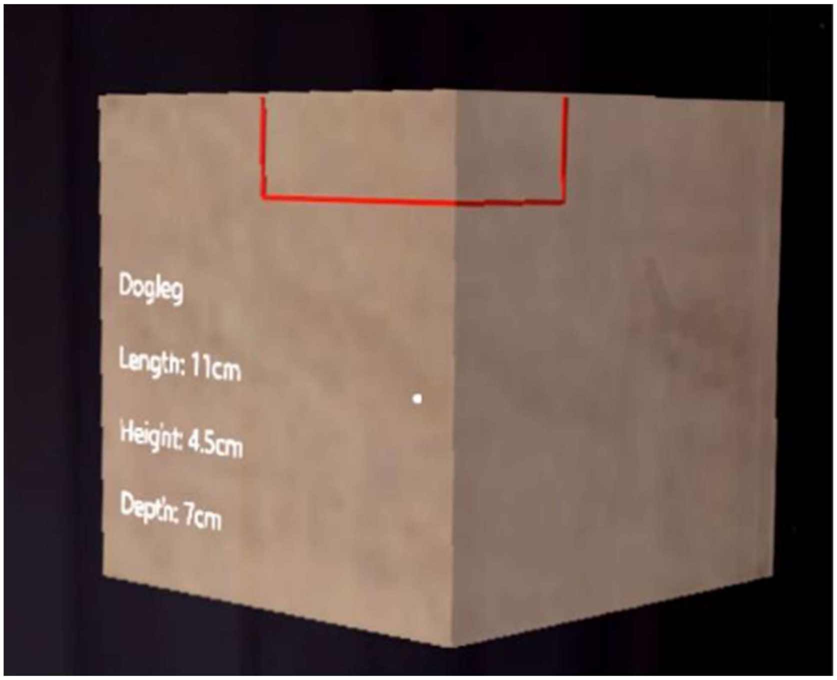


Figure 36: Mission display [6]

5.4.4 Marking Out

The virtual block is marked out using the virtual marker and ruler tools, shown in the MR app in Figure 37, and the desktop app and real life procedure shown in Figure 38. These are controlled by the HoloLens' gesture commands. The ruler uses the tap to place control scheme, to ensure the ruler can "snap" to the face of the block. The marker uses the drag and hold control scheme, allowing free movement by the user. The marker will only draw on the block when the two objects collide. The colour change is performed by a shader operation on each individual block the marker collides with.

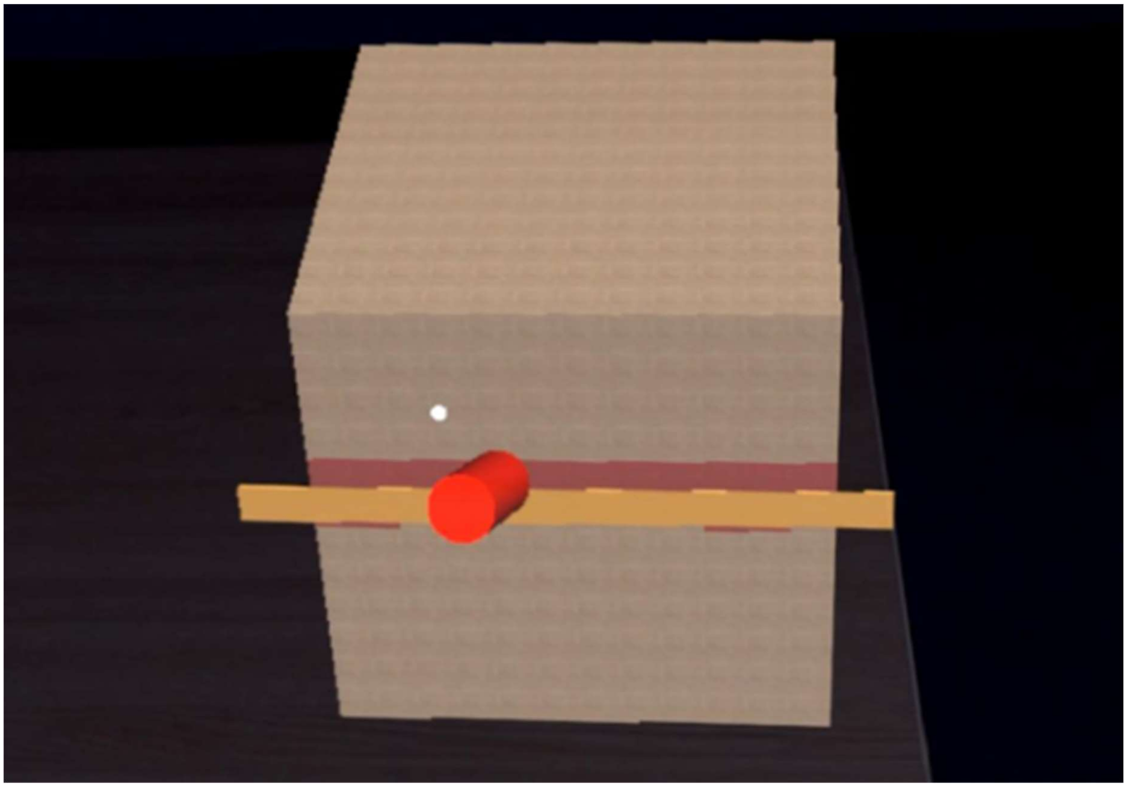


Figure 37: Marking out with virtual tools [6]

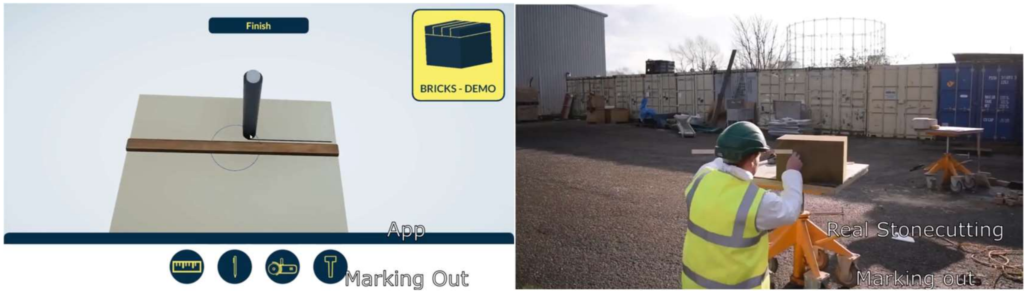


Figure 38: PC App and real marking out

5.4.5 Grinding

A real stone grinder with an image target attached to the cutting blade is used to cut the virtual stone block. The image target placement was decided by the field of view of the camera and the display on the HoloLens; when the cut is being performed, the end of the blade is within the operator's, and therefore the HoloLens', eyeline. The image must stay within the camera's field of view throughout the cutting operation to ensure tracking is accurate. To confirm detection of the blade, a white cylinder with the same proportions as the real blade is displayed. This procedure in MR is shown in Figure 39, and on desktop and in real life in Figure 40. While there was not enough scope to have realistic gyroscopic vibrations produced by the grinder, dust and a cutting sound are produced when the detected edge of the grinder blade intersects with the virtual stone block.

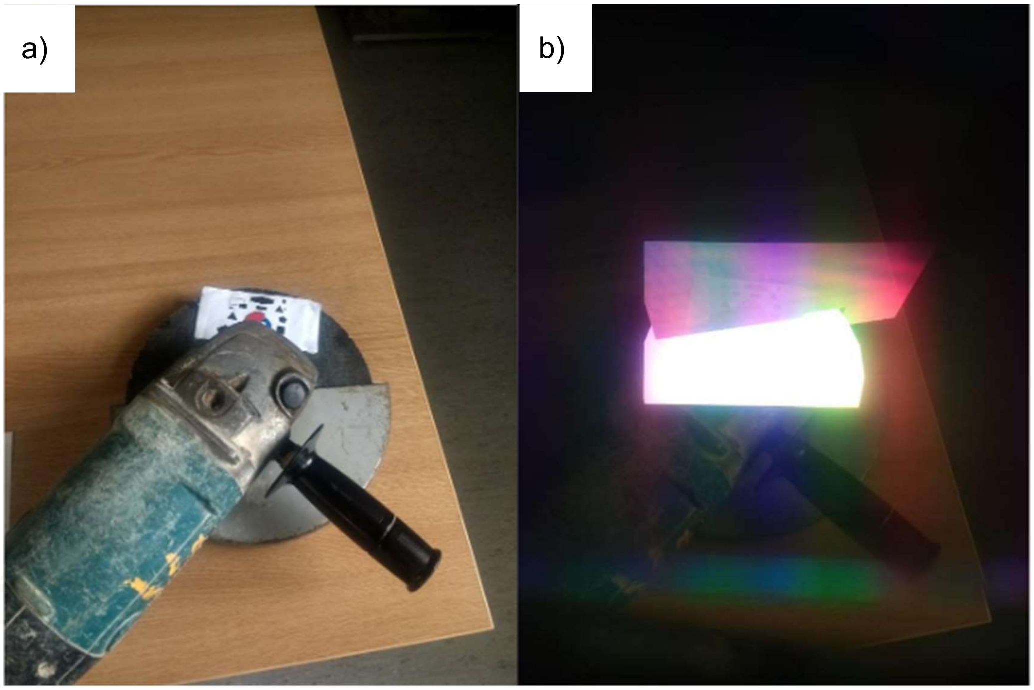


Figure 39: a) Grinder with image target b) Image target detected and grinding stone [6]

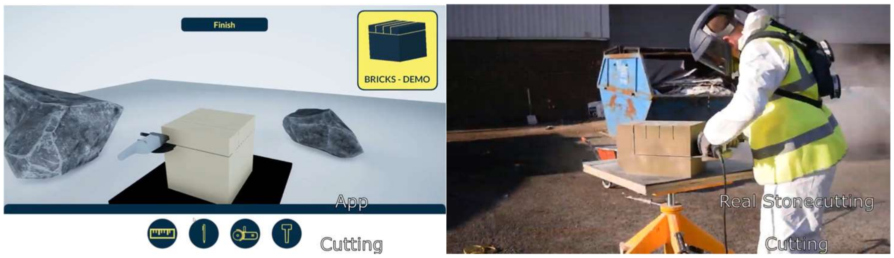


Figure 40: PC App and real cutting

5.4.6 Waste Removal

The waste removal process removes the “floating” blocks left behind by the cutting process to produce a clean cut, as seen in Figure 41. This process was simplified for performance reasons. The virtual hammer uses the drag and hold control scheme.

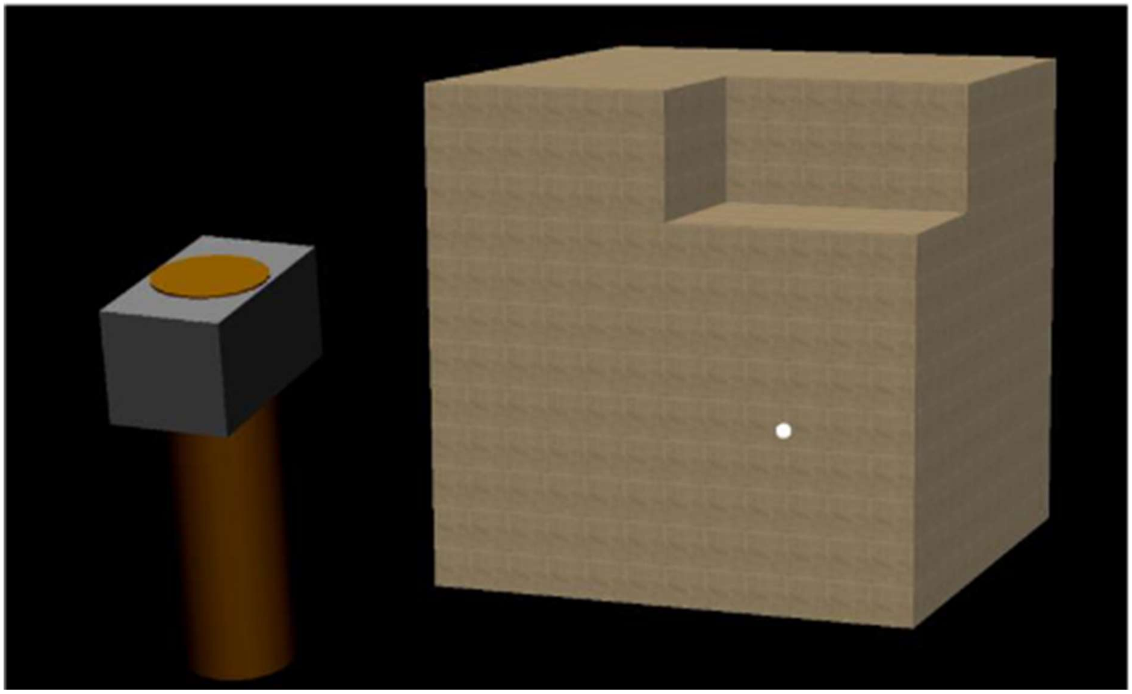


Figure 41: Waste removal with virtual hammer [6]

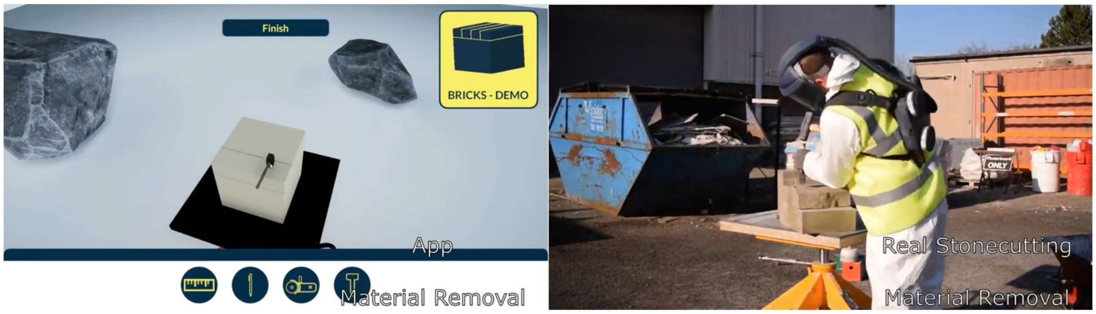


Figure 42: PC App and real waste removal

5.4.7 Tutor Usage

The application contains some facilities for use by the teaching staff. Staff can change the type of stone used and pick the required cut from a pre-set list by altering the configurational .json file, which changes the instructional block. In addition, an onboard replay of the full procedure carried out is stored in RAM during operation, allowing a tutor to watch the operation back by taking the headset and using the “Playback” toggle in the tool interface.

For the application, basic user telemetry on personal protective equipment (PPE) usage is sent in real time to a host PC via the use of a .JSON file, which is then interpreted by the server application on the host PC and a list of used PPE is displayed. This operation is completed as shown in Figure 43. Once a selection of PPE has been made, this prompts the application to attempt open a networking socket on a separate thread. If the attempt is successful, the application sends a “line”, which is a plain text string which follows JSON formatting conventions, to the host application on the host PC. The host PC then sends back an acknowledgement that the data has been received, and the communication ceases.

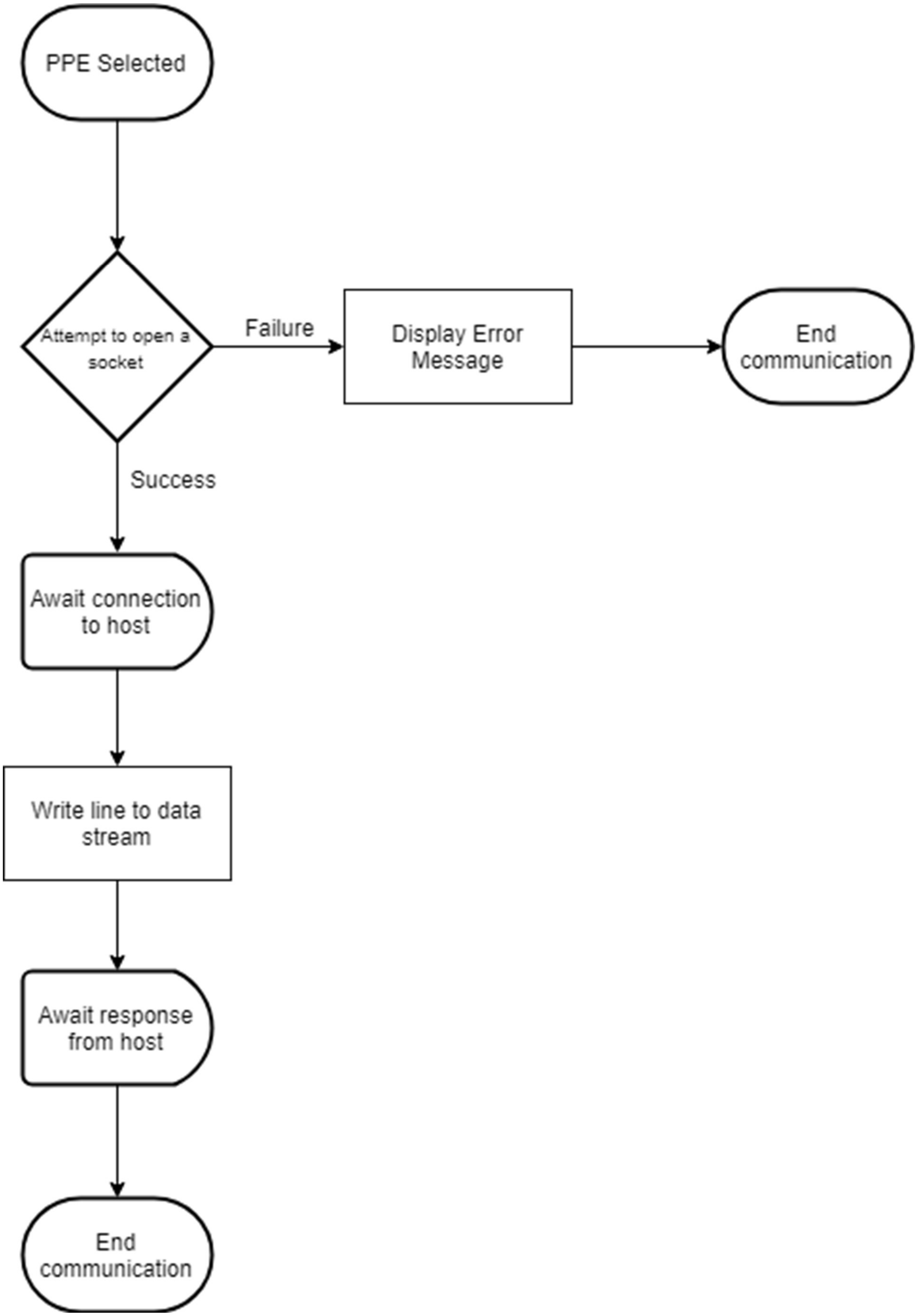


Figure 43: Telemetry communication flowchart

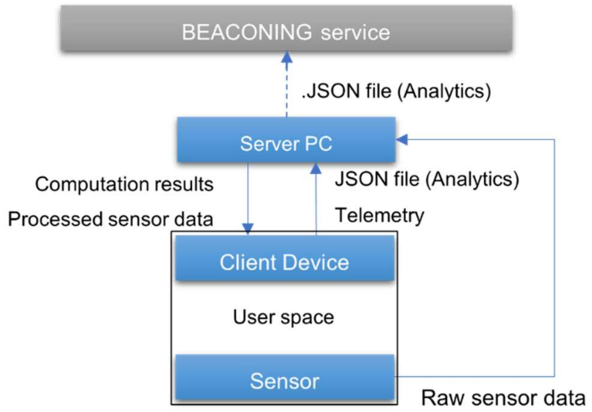
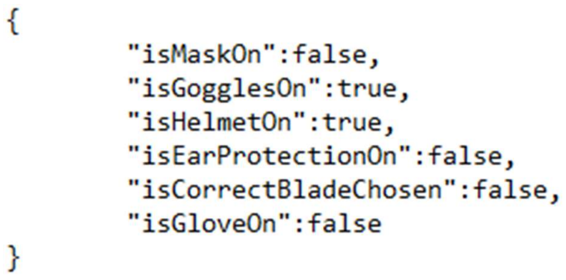


Figure 44: Telemetry data flowchart

Furthermore, this data can then be sent to the BEACONING service, shown in Figure 44. As a backup, a JSON file is also stored locally on the device which is formatted in the same manner. The host application can parse the JSON file and display in a readable format what PPE was selected. An example of the data string sent is shown in Figure 45.



```
{
        "isMaskOn":false,
        "isGogglesOn":true,
        "isHelmetOn":true,
        "isEarProtectionOn":false,
        "isCorrectBladeChosen":false,
        "isGloveOn":false
}
```

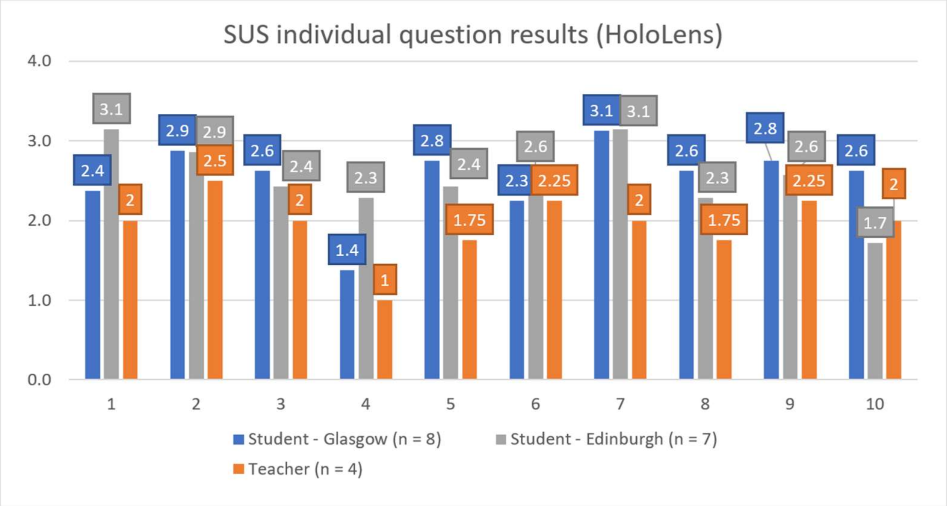
Figure 45: Example JSON data.

The replay file saved to the device and this analytics file both contribute to a collaborative and symbiotic approach to digital learning, whereby both the students and the teachers can gain knowledge from the student’s procedure. Reviewing the procedure allows a teacher to note any troublesome spots within the procedure, which can be remedied by an altered teaching procedure.

5.5 Findings

Test programs were carried out with stonemasonry students and teaching staff at City of Glasgow College and Edinburgh College to quantify the effectiveness of the application. These tests were centred purely on the usability of the application. The students and their tutors used both the computer-based VET application and the MR application. For the test, the participants were asked to complete a simple dogleg cut and given no further instruction. This was to allow the results to be collected based on the quality and intuitiveness of the in-application interface. Afterwards, participants were asked to fill out a generic System Usability Scale (SUS) questionnaire [193] for both the PC and HoloLens applications, and a long form questionnaire which was standard for the Beaconing program. The full questionnaires can be found in Section 10 Appendix A: VET Questionnaires. The combined class sizes were 15 students and four tutors, which represented the full cohort in Edinburgh and Glasgow for first year stonemasonry students in 2018. This small sample size means the results presented herein may be unreliable and vary with a larger sample size, which can be attained by running the experiments with further year groups.

These tests were carried out with a non-final version of the application, unfortunately there was no scope for further testing with the finalised version presented within this work, which was built upon feedback from these tests. Figure 46 shows the results from the SUS questionnaire. A score of 4 is the most positive response.



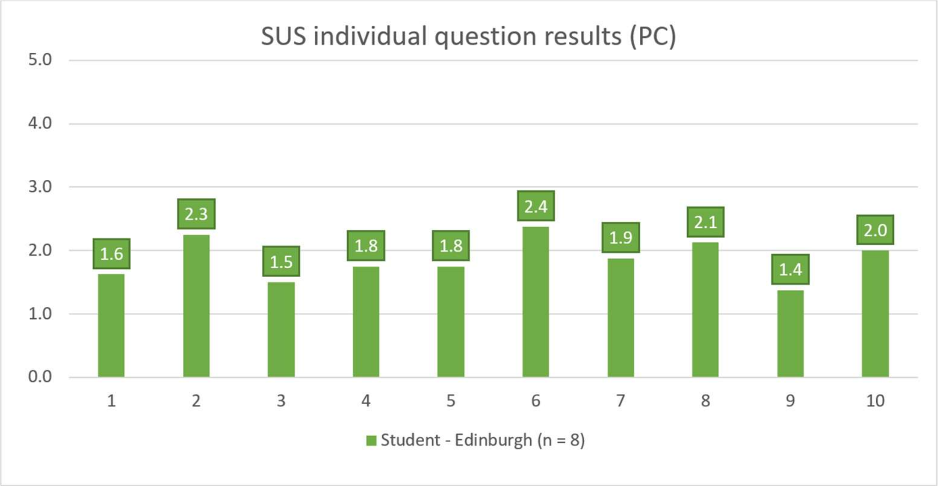


Figure 46: VET SUS questionnaire results – XR environment versus PC desktop environment

An average SUS score is 68 [194]. The formula used for calculations can be found in Section 10 Appendix A: VET Questionnaires. For students, a SUS score of 63.50 was recorded. For tutors, a SUS score of 48.75 was recorded. For the PC-based application, a SUS score of 43.57 was recorded, only by students in Edinburgh. The results recorded for both versions of the application were below the considered acceptable level of usability (SUS score 68). While the SUS questionnaire is a generic indication of usability, combined with the questionnaire it is possible to highlight problematic areas. Shortcomings were found with the application, the tracking methodology and the HoloLens itself for novice users.

5.6 Feedback

General feedback reinforced the concept of bringing interactive simulation applications into the learning process.

A common issue found during testing was the positioning of the headset on the user's head. As highlighted in 2.5.2 CD Gains in a Mixed Reality environment, the first model of HoloLens used has a limited field of view. Once positioned correctly on the user’s head, the OS cursor (visible as a white dot as seen in Figure 33 through Figure 41) becomes visible in the centre of the user's vision. On initial attempts at fitting the headset, almost every user reported issues with being able to see the cursor. Participants also noticed the obvious edges of the display area of the HoloLens and struggled to locate the block in the room. For the image-based tracking, there was some difficulty at positioning the grinder at an angle where the HoloLens’ cameras could see the tracking target, which prevented the tracking from working consistently. All these problems were exacerbated by the inability for the tester to see what the user was seeing in the headset. This was borne out in the comparatively low score for question 4 for the SUS questionnaire, "*I think that I would need the support of a technical person to be able to use this system*", indicating that users agreed that they would need technical help to use the system comfortably. This issue has been partly solved by the release of the HoloLens 2, which has a wider camera field of view for image tracking. It was incidentally observed that most participants were hesitant to walk around with the headset on, asking questions as to whether they were free to walk around.

For the PC application, it was clear by the significantly lower SUS score that there were usability problems. The questionnaire highlighted the use of the 2D mouse input device for the 3D space of the application was the main issue when compared to the HoloLens application.

The completion of the SUS informed areas for improvement in the application. To address the challenge highlighted by question 4, a static "toolbox" was implemented after users complained of the difficulty of finding tools suspended in space. Teachers raised the question of having a replay tool in the application, which was implemented and allows a user to watch back the process carried out by a previous user. The lung graphic and functionality were added to reinforce the importance of wearing the correct PPE. Performance optimisations were implemented, using a different graphical shader on materials which improved performance in conjunction with firmware updates to the HoloLens itself, which took the application from 15 frames per second to the display's native 60 frames per second, with improved battery life.

A physics-based system for waste removal was trialled, whereby each cut section would "loosen" the stone above it to simulate the cut section crumbling from lack of support, enabling the simulation of a clean-up process involving dusting the virtual blocks from the real surface on which the operation was performed. Achieving this would have enabled the application to conform more fully to COSVR195. However, in the time of this project it was not possible to make this performant enough for use.

Further improvements could be made to this system through better use of CD gains. More study into optimal CD gain for purely virtual interactions would enable more intuitive operation of the tools contained within the application. Additionally, it would be possible to have more real tracked tools instead to operate with the virtual environment.

5.7 Summary

The successful development of a mixed reality simulation game for vocational education utilising a real tool filled the identified research gap of the use of extended reality tools in VET. Positive feedback from students indicated that the proposed solution was more desired than a desktop based equivalent system. This work has been cited in Schuster et al. [195] and Lasala et al. [196] for its novel use of the HoloLens, Vigoroso et al. [197] for exploring the use of rewards to increasing engagement and Erturk et al. [198] for the use of a cyber-physical systems to allow students to learn without risking their safety. This work also proves that it is possible to have a symbiotic human-systems interaction in this field, with student procedures potentially being used to alter the teaching of the material. However, before this application, or any application involving MR for VET, can be deployed, there are some further challenges which must be addressed.

Future work in this area includes haptic feedback from the grinder. It is possible to replace the metal disc in the grinder with a safer rubber equivalent, and then use the motor to spin this replacement disc, applying braking forces when the grinder hits the virtual block, to increase the level of realism of the simulation. A major factor in stone grinding incidents is the “kick back” effect from the braking forces induced by the intersection with the stone, so this is a critical safety area which is currently impossible to train for without using a real tool, which is not a part of the current curriculum in Scottish further education.

Another area of future work is the development of the gamification mechanics. This could make the application more engaging for students and provide them with more immediate feedback of their actions. For example, a score could be calculated for the accuracy of the cut.

Real-time telemetry transfer between the student and a host teacher application would enable for real time collaboration between both parties. This system could not be developed in time for the project, but such a system would further enhance the symbiotic nature of the application.

In conclusion, the successful mirroring of the relevant educational standards (COSVR195) in an extended reality, cyber-physical twin-based training environment confirms that it is possible to enable a technology assisted learning tool for VET which accounts for extended reality, collaboration and data synchronisation. The feedback obtained indicates clear and identified avenues for future improvement in this specific application. In terms of the overall framework, this application laid the foundation for analytics transfer, extended reality interactions and human-system symbiosis. The quantitative data collected showed more work needed to be done to truly extend reality and fully immerse the students in their education. Additionally, the light usage of data transfer features (not time-critical) required further work to be performed on this aspect of CyPhER. Despite these challenges, the results acquired in terms of user satisfaction with the system and successful prototype of an application based around cyber-physical manipulations in XR begin to confirm the working hypothesis stated in Section 1.2 Hypothesis.

6 Implementation of CyPhER in Digital Twin Applications

This chapter will focus on the implementation of CyPhER in digital twin applications. This implementation contains the final, presented version of CyPhER. The DTs were developed to tackle the technology gap in data transfer between autonomous systems and scalable devices, with edge devices and stationary workstations considered, with the provision for two-way control between the twin and the asset.

The aim of this work is to provide a symbiotic, cyber-physical twin using the digital thread framework, to enable human-systems symbiosis within offshore autonomous robotics. Extending reality is also considered through the differing user interfaces presented for each application, with the possibility for real time human-machine interaction.

6.1 Application Domain

This application was developed for the DT domain. These applications generally have an industrial focus, specifically in the field of autonomous systems and robotics. These applications focus on remote and scalable computing needs, with specific focus on Beyond Visual Line-Of-Sight (BVLOS) systems. Two-way control is a constant in the implementations, with the digital twin feeding forward to the autonomous system, which feeds back to the twin. In this way, the twin both reflects the real-world condition and is used as a preview for desired changes to the real-world asset. For the development of CyPhER, this domain forced the improvement of the practical implementation of the framework, in terms of network communications, data transfer and remote human-system interaction (even if the input methodologies themselves were not the focus of this part of the research).

The DT was developed as part of a demonstrator for system of systems design. It tackles the identified gaps of symbiotic DTs and interoperable twins which are application, platform and data agnostic.. This work is covered in detail in Mitchell et al. [1]. The aim of this work is to enable resident robotics in offshore environments without the need for human intervention. To achieve this, the systems must collaborate, cooperate and corroborate to ensure mission success. The Symbiotic System Of Systems Approach (SSOSA) aims to produce systems which act symbiotically, involving collaboration, cooperation and corroboration of each aspect of the system. The DT operates in the User Interface layer of the SSOSA, providing the interface between the human and the hardware, shown in Figure 47.

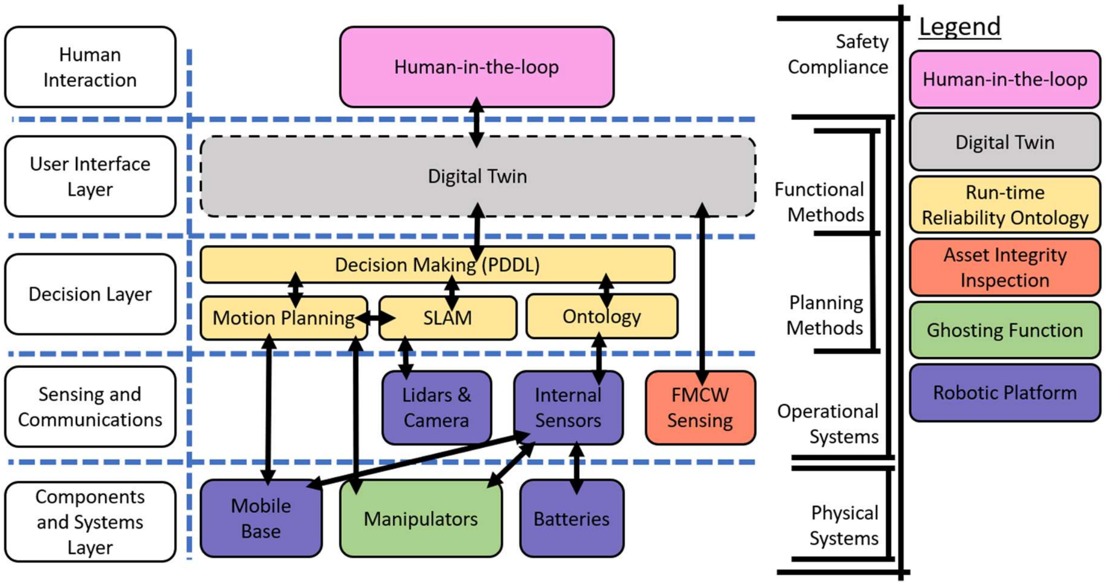


Figure 47: System integration process of the SSOSA for the robotic platform. The DT, highlighted with a dashed box, is in the user interface layer, interfacing between the human-in-the-loop, decision making and sensing.

To enable SSOSA, the human-machine interface is provided through a digital twin. Figure 48 shows the proposed conceptual symbiotic architecture design. A bidirectional knowledge exchange between a remote observer and the resident systems is provided through the digital twin, allowing direct interaction with asset integrity information, the robotic platforms, and the run-time reliability ontology.

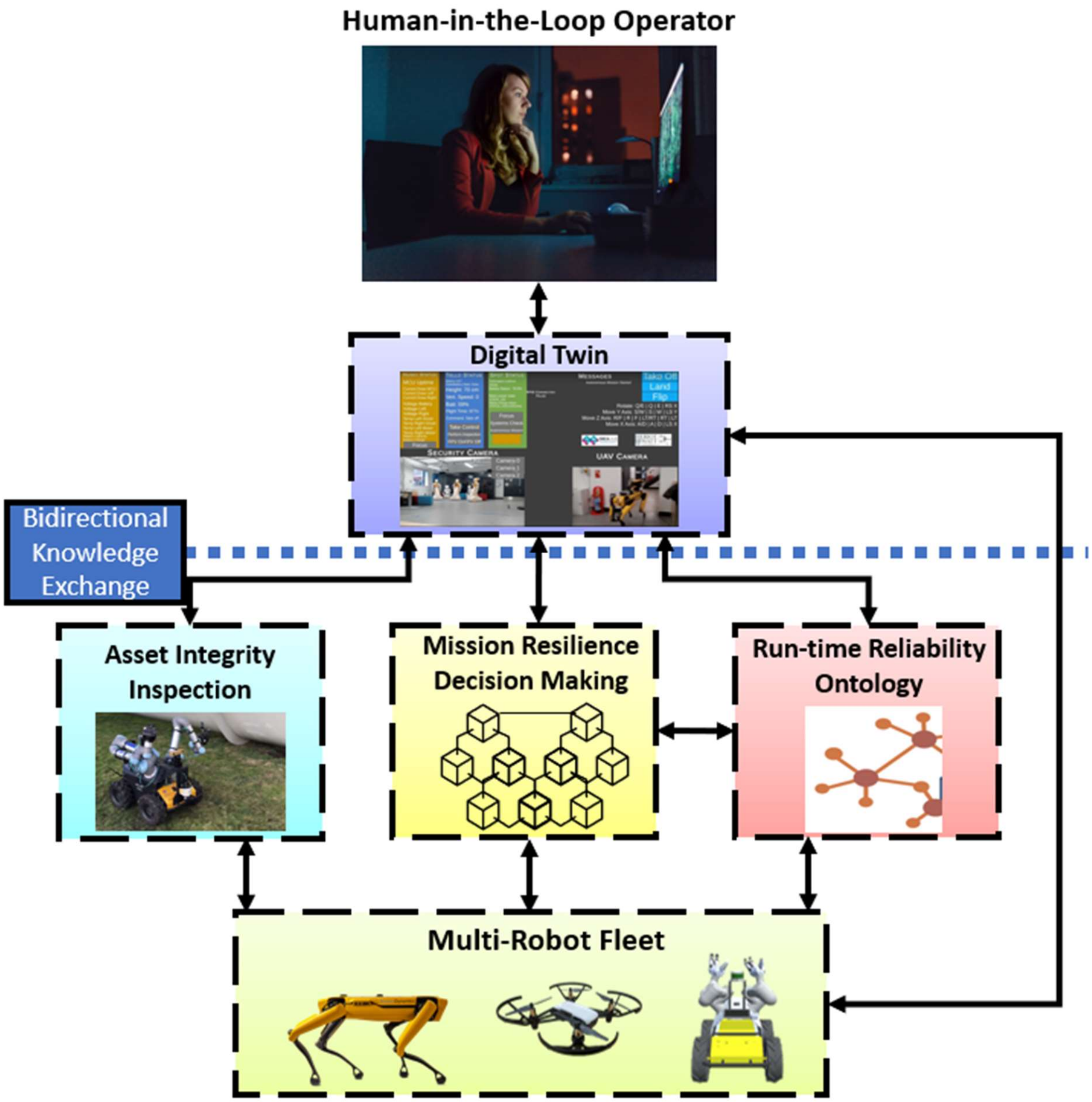


Figure 48: Application design for symbiotic architecture [1]. The digital twin work focusses on the interaction with the Human-In-The-Loop Operator to facilitate bidirectional knowledge exchange.

6.2 Application Flow

These applications were developed with the same framework between them. As-built data is used to generate a simulated, virtual asset to provide a system or infrastructural overview. Human-machine interaction is provided through a GUI, which changes depending on the input requirements of the device in use. The GUI allows visualisations and manipulation of digitalised assets. These manipulations can be viewed and confirmed in the GUI before being sent to the autonomous system.

For scalability purposes, CyPhER supports the synchronous transmission and reception of data between numerous client and host devices. To achieve this, unique asset IDs and timestamps are used, and all communication is sent through a TCP network. A demonstration of this topology is available in Figure 49. This configuration allows data to be sent and received synchronously whilst being routed through a TCP router. In this case, scalability is ensured through the capability of the network to deal with devices being connected or disconnected whilst operations are running. All the sending and receiving devices can range from portable, low powered edge devices to large, stationary workstations. The asset connects to each device individually and can send and receive information to and from the devices. Structuring the data transfer in this way allows optimisation depending on the available computing capability.

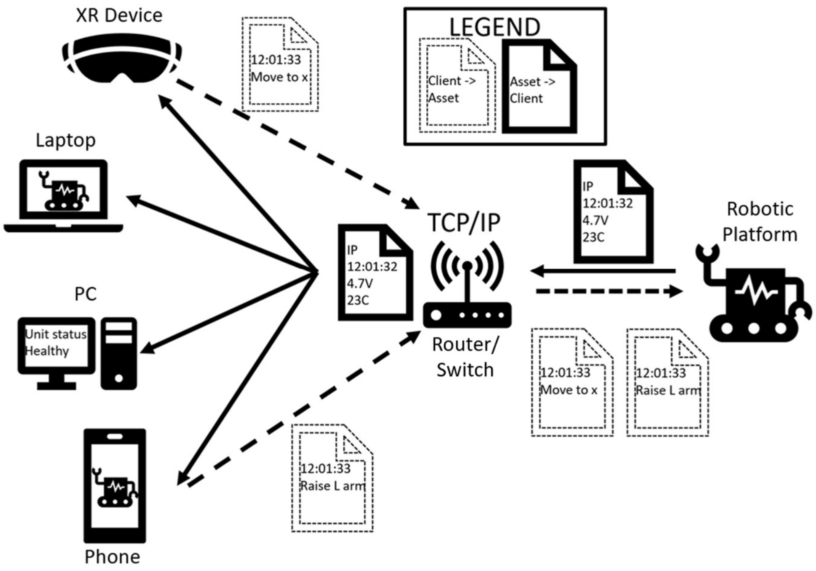


Figure 49: Basic network overview of one implementation of proposed DT infrastructure. Timestamped information flows freely to and from an asset (robot), through to multiple devices synchronously, transported by TCP.

Alternatively, it is possible to structure the network with a central server. The central server can be locally managed or from a cloud computing service such as Microsoft Azure or Amazon Web Services. This can be necessary in cases where security restrictions on an asset prevent direct communication with the client device. This also reduces the burden on the asset side, as the central server can interpret raw asset telemetry into a readable format for the edge device.

This reduces both computational and network bandwidth cost of operations on both the asset and client side.

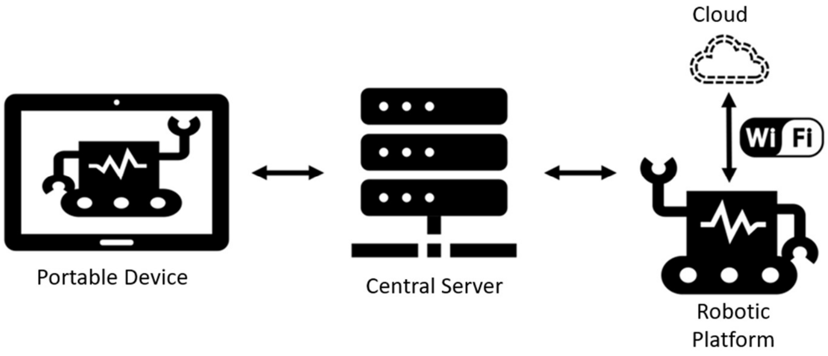


Figure 50: An overview of a two-way DT system with a central server and an edge device on the asset.

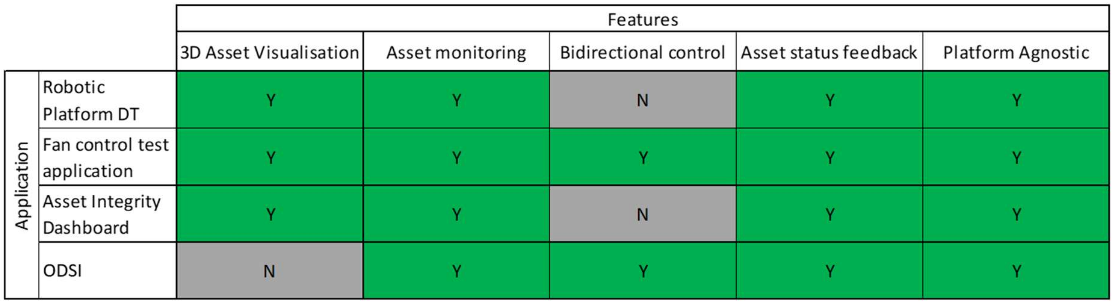
6.3 Application Development

Four applications were developed in this domain:

- DT of a robotic platform.
- Fan control test application
- FMCW scanning of a wind turbine blade.
- Operational Decision Support Interface for remote asset management – see chapter 7.

All applications were developed in Unity3D 2018.4.1f1 C#, except the ODSI which was developed in 2020.13.1f1 C#, as it was developed when this was the newest, stable long term service version of Unity available. Using a newer version of Unity provided benefits such as an improved development interface and fewer issues with Unity itself, while causing minimal compatibility issues. For DTs, there is a precedent for using Unity3D for visualisation processes [199], [200], [201], [202]. Unity was chosen for its interoperability as highlighted in Section 3.3.4 Ensuring Device Agnosticism, allowing any developed DTs to be compatible with as much available hardware as possible. It has integrated .NET Sockets and Threading support, extensive documentation, integrated scalability options such as a reduction in rendering quality for low powered devices, support for Computer Aided Design (CAD) models FBX and OBJ formats and integrated compatibility for multiple input methods. This enables 3D asset representation and control across a wide variety of devices and a rapid deployment process due to not needing to rewrite the entire application for each device – only input methods and GUI layouts differ. Furthermore, this also allowed the basic backend communication code to remain the same between each implementation, the main differences in each application being the method of displaying information and control. The features of these applications are summarised in Table 13. The work performed on one application fed directly into the others. Referring to Figure 48, only the fan control test application and the ODSI fully encompass a symbiotic architecture. The Robotic Platform DT was developed as a proof-of-concept and therefore only receives information from the robot, however the work done to achieve this was re-used in the test application and ODSI. The Asset Integrity Dashboard is a concept developed to explore the potential of using CyPhER to produce actionable insights based on raw data so also does not contain any bidirectional control. The ODSI forgoes 3D asset visualisation due to the usage of runtime camera footage, allowing the operator to always see the real asset. Referring to Figure 16, the DTs contained within the ODSI and fan control application are stage 4 DTs progressing from the stage 1 DT found within the Robotic Platform DT.

Table 13: DT application features

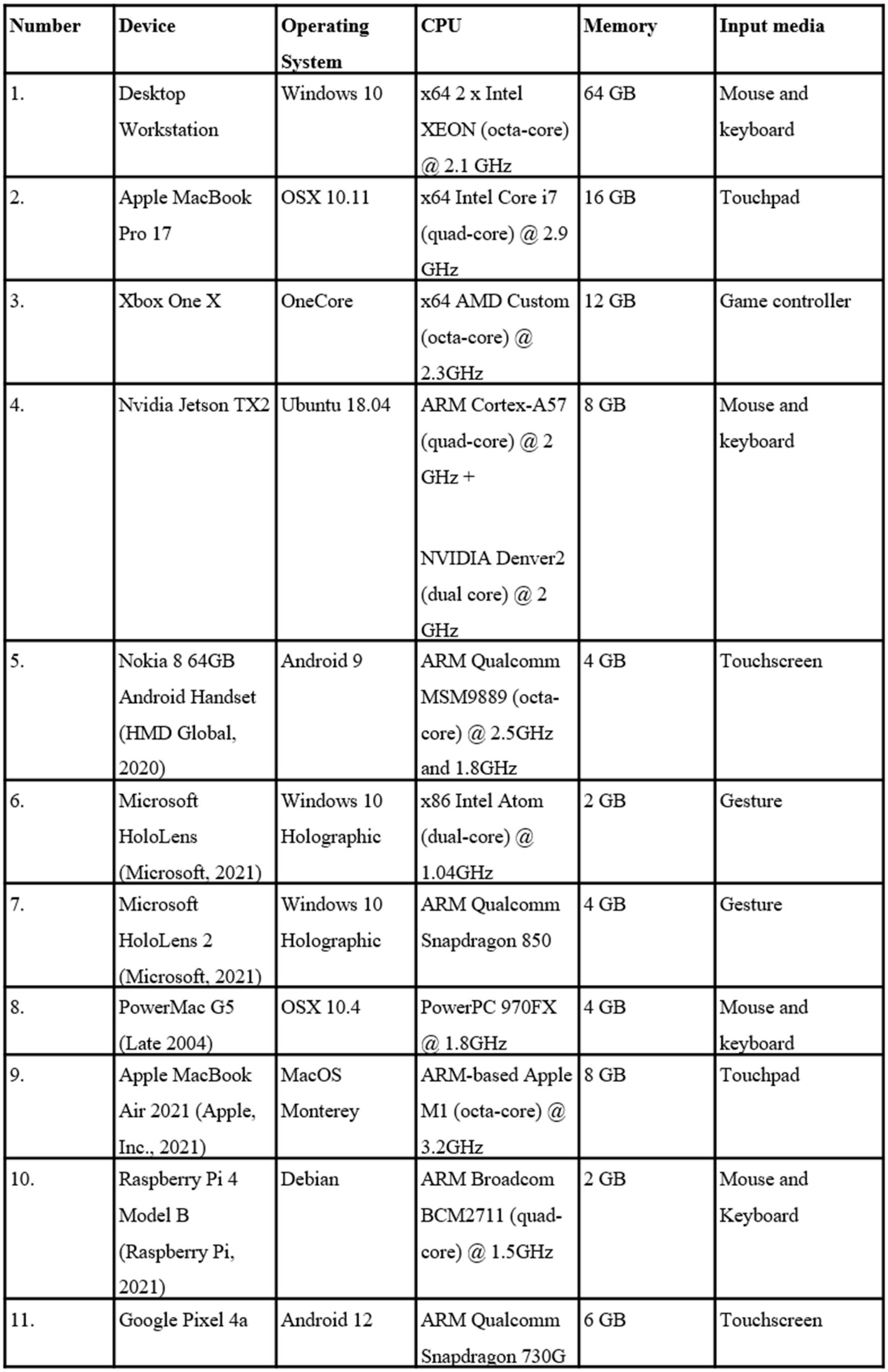


		Features				
		3D Asset Visualisation	Asset monitoring	Bidirectional control	Asset status feedback	Platform Agnostic
Application	Robotic Platform DT	Y	Y	N	Y	Y
	Fan control test application	Y	Y	Y	Y	Y
	Asset Integrity Dashboard	Y	Y	N	Y	Y
	ODSI	N	Y	Y	Y	Y

6.4 Application Implementations

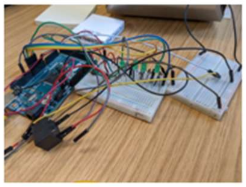
The devices to which the applications were deployed are shown in Table 14. These devices span various distinct computing architectures. As time passes, it can be assumed that more powerful hardware will continue to be developed at a lower cost and with a lower physical footprint. It is important such a framework can operate on a wide range of hardware. The prevalence of capable, low-cost, small edge devices such as the Nvidia Jetson encourage the use of such devices for a DT, e.g., for environmental monitoring. These devices can also be found inside modern robotic platforms. Operating system agnosticism is important for the development of CyPhER, while many robotic platforms run Unix based systems, Windows workstations are still prevalent. In addition, more alternative architectures to x64 commonly found on Unix/Windows based systems are beginning to emerge in the space. Phone architectures are commonly ARM based, and more edge devices are beginning to use this architecture, as well as all Apple Mac products post 2021. These listed implementations were performed to demonstrate the versatility of CyPhER, through age and capability of hardware, proving its interoperability and adaptability to different platform capabilities and forms. This tackles the identified challenge for interoperable, standardised digital twins which are application, platform and data agnostic. The twinned hardware is described in Table 15. The computer case fan and Arduino were chosen as simple, low-cost equipment to prove out connectivity and trial different DT features. The robotic platforms were chosen as part of the industry led resilience demonstration project.

Table 14: DT deployed hardware comparison



Number	Device	Operating System	CPU	Memory	Input media
1.	Desktop Workstation	Windows 10	x64 2 x Intel XEON (octa-core) @ 2.1 GHz	64 GB	Mouse and keyboard
2.	Apple MacBook Pro 17	OSX 10.11	x64 Intel Core i7 (quad-core) @ 2.9 GHz	16 GB	Touchpad
3.	Xbox One X	OneCore	x64 AMD Custom (octa-core) @ 2.3GHz	12 GB	Game controller
4.	Nvidia Jetson TX2	Ubuntu 18.04	ARM Cortex-A57 (quad-core) @ 2 GHz + NVIDIA Denver2 (dual core) @ 2 GHz	8 GB	Mouse and keyboard
5.	Nokia 8 64GB Android Handset (HMD Global, 2020)	Android 9	ARM Qualcomm MSM9889 (octa-core) @ 2.5GHz and 1.8GHz	4 GB	Touchscreen
6.	Microsoft HoloLens (Microsoft, 2021)	Windows 10 Holographic	x86 Intel Atom (dual-core) @ 1.04GHz	2 GB	Gesture
7.	Microsoft HoloLens 2 (Microsoft, 2021)	Windows 10 Holographic	ARM Qualcomm Snapdragon 850	4 GB	Gesture
8.	PowerMac G5 (Late 2004)	OSX 10.4	PowerPC 970FX @ 1.8GHz	4 GB	Mouse and keyboard
9.	Apple MacBook Air 2021 (Apple, Inc., 2021)	MacOS Monterey	ARM-based Apple M1 (octa-core) @ 3.2GHz	8 GB	Touchpad
10.	Raspberry Pi 4 Model B (Raspberry Pi, 2021)	Debian	ARM Broadcom BCM2711 (quad-core) @ 1.5GHz	2 GB	Mouse and Keyboard
11.	Google Pixel 4a	Android 12	ARM Qualcomm Snapdragon 730G	6 GB	Touchscreen

Table 15: Twinned hardware for digital twin.

Hardware	Description	Image
Computer case fan	A standard computer case fan, with 5V input and output.	
Arduino with breadboard	Used to control and read the fan, the voltage input being changed to rpm, then send the data to the attached computer.	
DJI Tello	Off-the-shelf budget-oriented Unmanned Aerial Vehicle (UAV) with one forward facing video camera and two underbody IR sensors to determine altitude.	
Husky A200 with Dual UR-5 Arms	Off-the-shelf wheeled robotic platform (Husky) with a custom fitted dual arm attachment for manipulation. Uses Robot Operating System (ROS).	
Boston Dynamics Spot	Off-the-shelf legged robotic platform with an arm attachment for manipulation. Uses a python-based Software Development Kit (SDK).	

6.5 Robotic Platform Digital Twin

This implementation was developed for the Blyth Offshore Demonstrator in 2020. For this demonstrator, a DT was created which allowed a robotic platform involving a Husky A200 with dual UR-5 arms to be monitored through different devices. The robotic platform is shown in Figure 51.

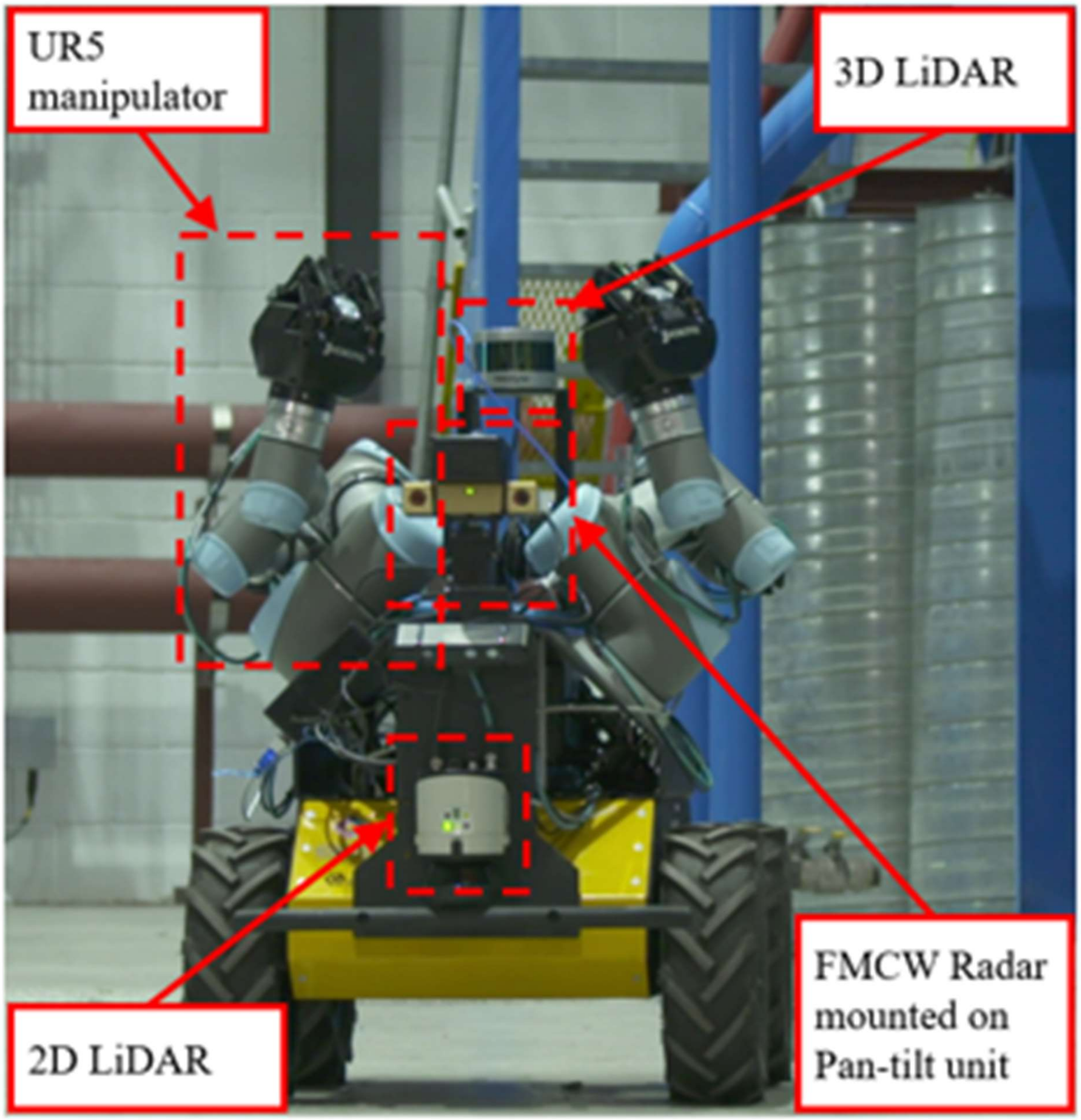


Figure 51: Husky A200 with Dual UR-5 attachments.

The objective of the demonstrator was to carry out an asset integrity inspection mission in an offshore analogue environment. The robotic platform was to start from a base point, transit to and perform two asset integrity scans using an FMCW radar, with confined space navigation and three pre-determined failure modes, which would be triggered as the platform reached different points, before returning to the base point. The mission plan is shown in Figure 52.

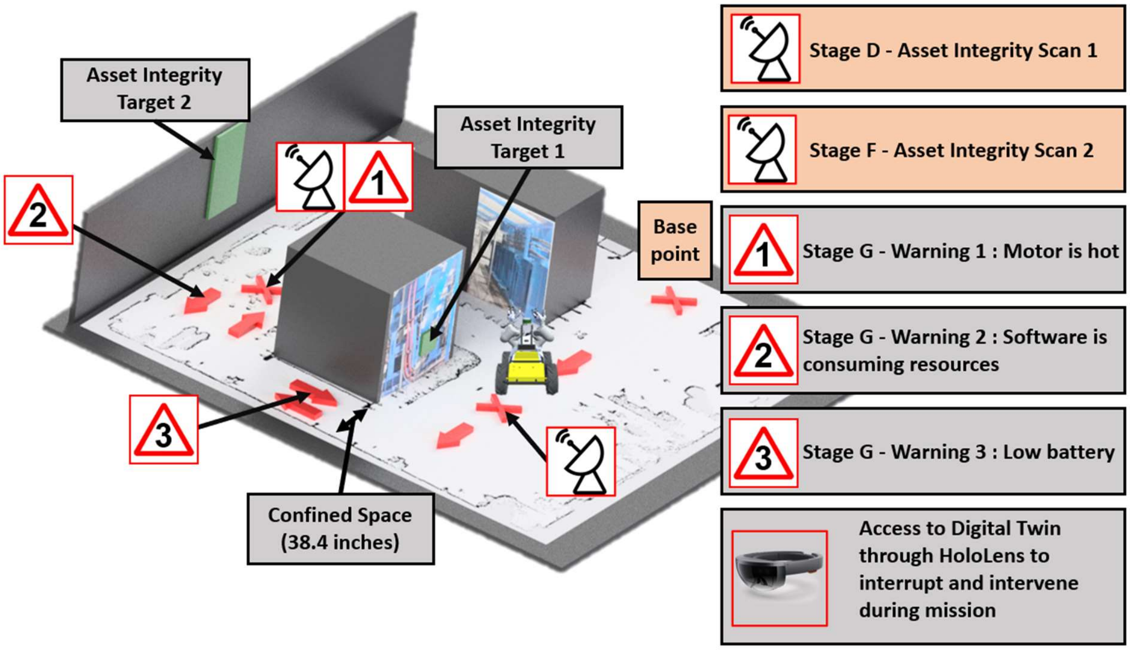


Figure 52: Blyth Offshore Demonstrator mission plan.

For the demonstrator, three different DT implementations were developed, as explained in Figure 53.

- A is a demonstration of the physical twin, which in this application is the Husky platform.
- B is a purely desktop-based DT, intended for a remote operator at a base station to view critical, human readable telemetry information from the robotic platform.
- C shows an AR twin of the platform, this is a 3D model of the robot with telemetry overlaid, viewed through the HoloLens in the real world. This could be used by an operator in either a base station or on-site, with the 3D model providing a visual reference of the platform. The 3D model itself does not have any interaction with the real world – the use of AR simply allows a user to explore the 3D model in real space.
- D shows the mixed reality twin, using QR codes stationed on the physical robot to show virtual informational overlays in the HoloLens. This would be used for on-site monitoring of the platform, allowing an operator to inspect various components of the robot by looking at them.

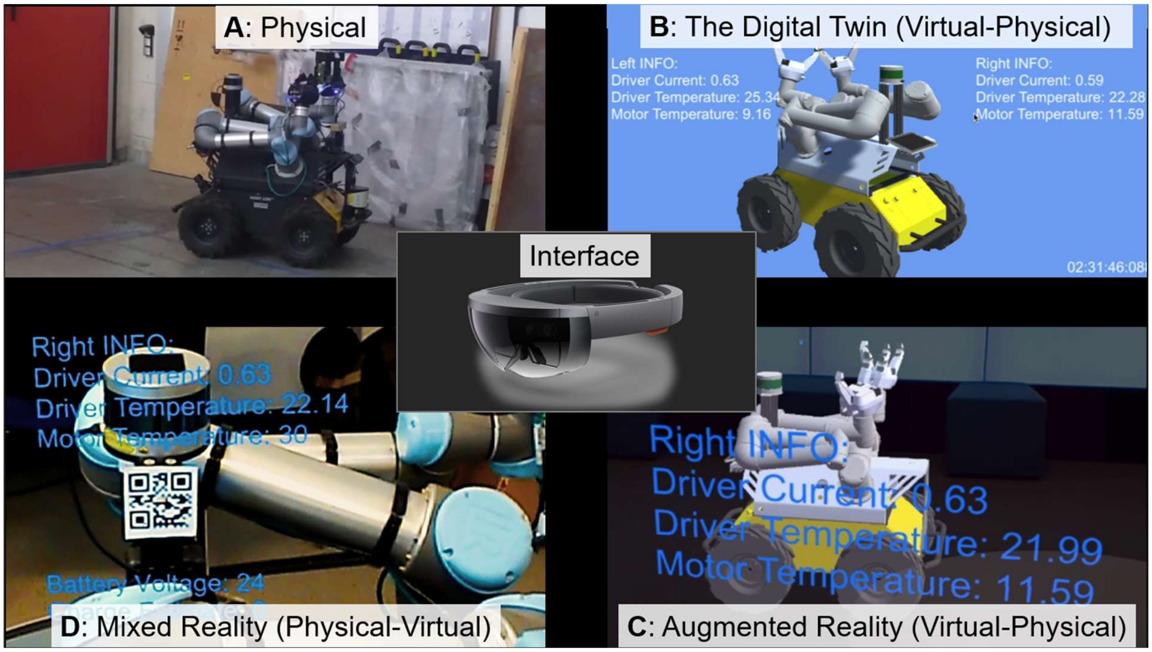


Figure 53: A: Husky A200 with Dual UR-5. B: Computer based DT. C: HoloLens based augmented reality DT. D: HoloLens based mixed reality DT.

This DT implementation also features a ghosting functionality. Whilst full two-way control could not be implemented in time for the demonstrator, this ghost allows the operator to see the manipulations required for the UR-5 arms to reach a desired position. The data for the ghosting operation is generated from the provided description of the robot, which contains the rotational limits for each axis of the arm. This is beneficial for visualisation purposes, as it allows an operator to determine if there is enough space for the proposed operation. The operator would choose a location to move the arms to, view the ghost animation of the proposed movement, then “confirm” the operation, and the instruction would be sent to the physical robot. This operation was developed to improve operator trust in the DT, as changes to the real robot would be reflected in the DT and vice versa. An image of this is presented in Figure 54.

Figure 54: Preview functionality of DT "Ghosting" feature, highlighting the position of the translucent arm, which is the planned movement.

The DT also implements a colour coding system for showing faults on the robotic platform, which was critical to the demonstrator. By changing the colour of the affected component, attention is drawn to the location of the fault, giving the operator instant feedback on the status of the component. An example of this coding is shown in Figure 55. Furthermore, error messages can be shown in addition to this colour coding as demonstrated in Figure 56. This information is sent to the DT from the robotic platform in the form of a short string, which is interpreted by the server in the DT and displayed as human readable text.

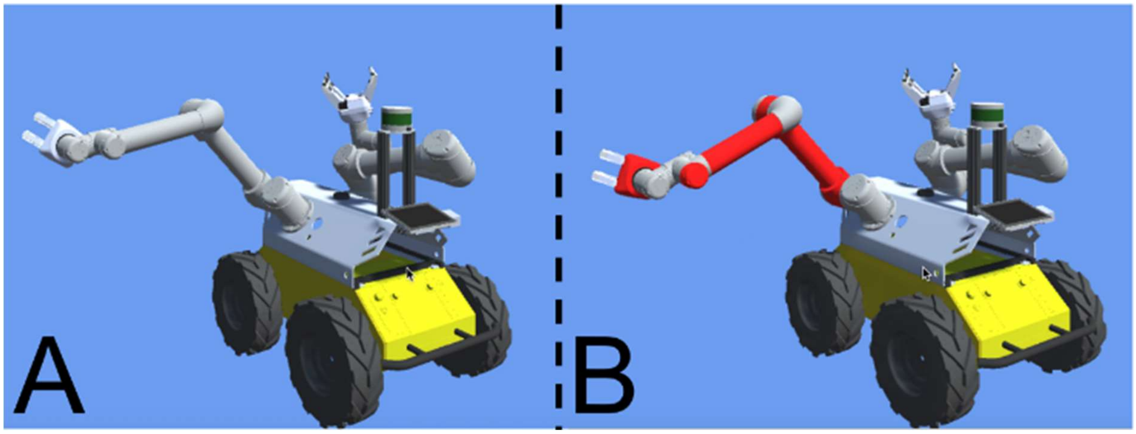
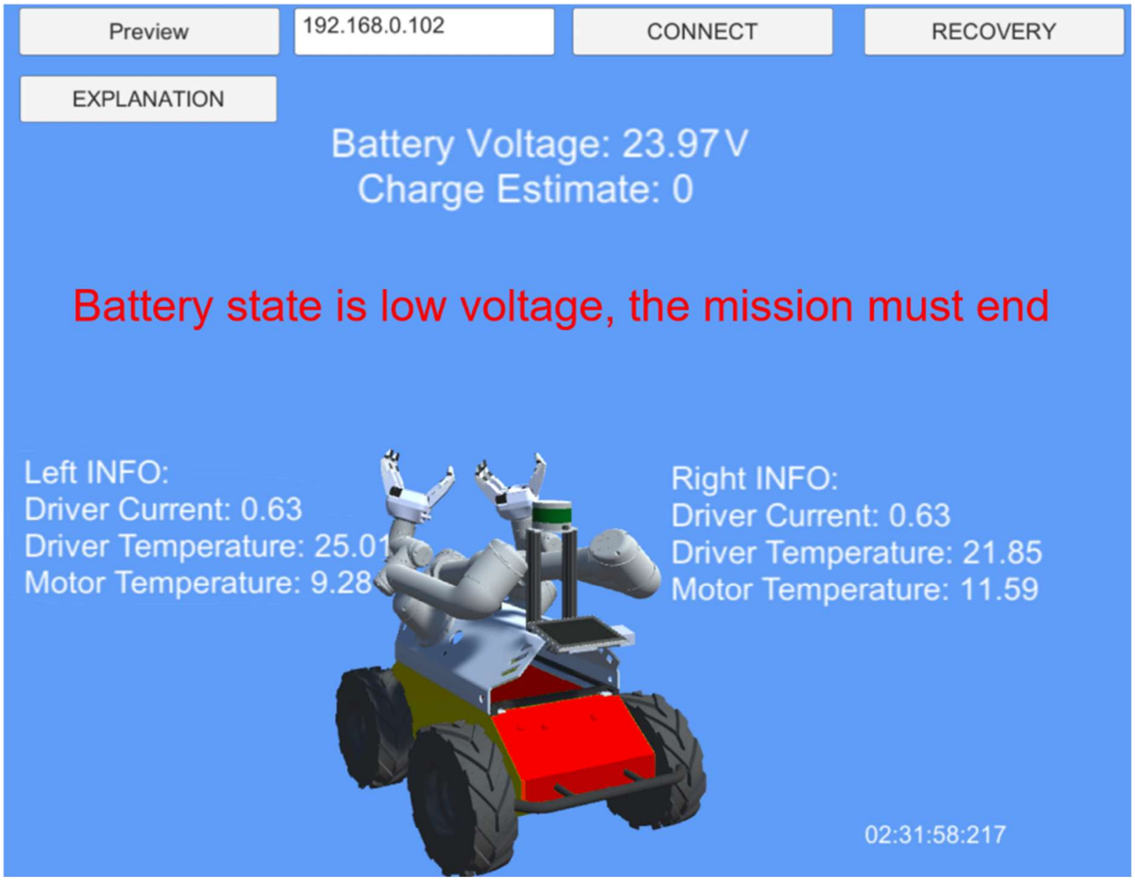


Figure 55: A: DT. B: DT displaying detected fault in the arm.



192.168.0.102

Battery Voltage: 23.97V
Charge Estimate: 0

Battery state is low voltage, the mission must end

Left INFO:
Driver Current: 0.63
Driver Temperature: 25.01
Motor Temperature: 9.28

Right INFO:
Driver Current: 0.63
Driver Temperature: 21.85
Motor Temperature: 11.59

02:31:58:217

Figure 56: DT displaying low battery error message.

6.6 Fan Control Test Application

To prove out the performance and evaluate the use cases for this system, a CPS implementation of the DT was created. This implementation needed to be flexible, low cost and electronically simple to ensure any testing was to prove out the DT architecture and not the robustness of the electrical system. This testing application was a DT of a small computer case fan. This application uses the full DT feature set, as described in Table 13. Simulating the full suite of features allows the application to be a “worst case” scenario, ensuring all features work as intended and placing maximum load on the underlying framework. The circuit layout of the system is shown in Figure 57. Using an Arduino interface, the computer case fan is connected to a breadboard via a KS2E-M-DCS relay. For local control of the fan, there are two buttons to turn the fan on and off, and speed lights which show the rotational speed in 25% increments of the maximum speed. The buttons and lights are connected to 102Ω resistors. A thermistor is also present in the circuit. The Arduino was connected to a host laptop using a USB connection. To ensure correct circuit operation, an oscilloscope was used.

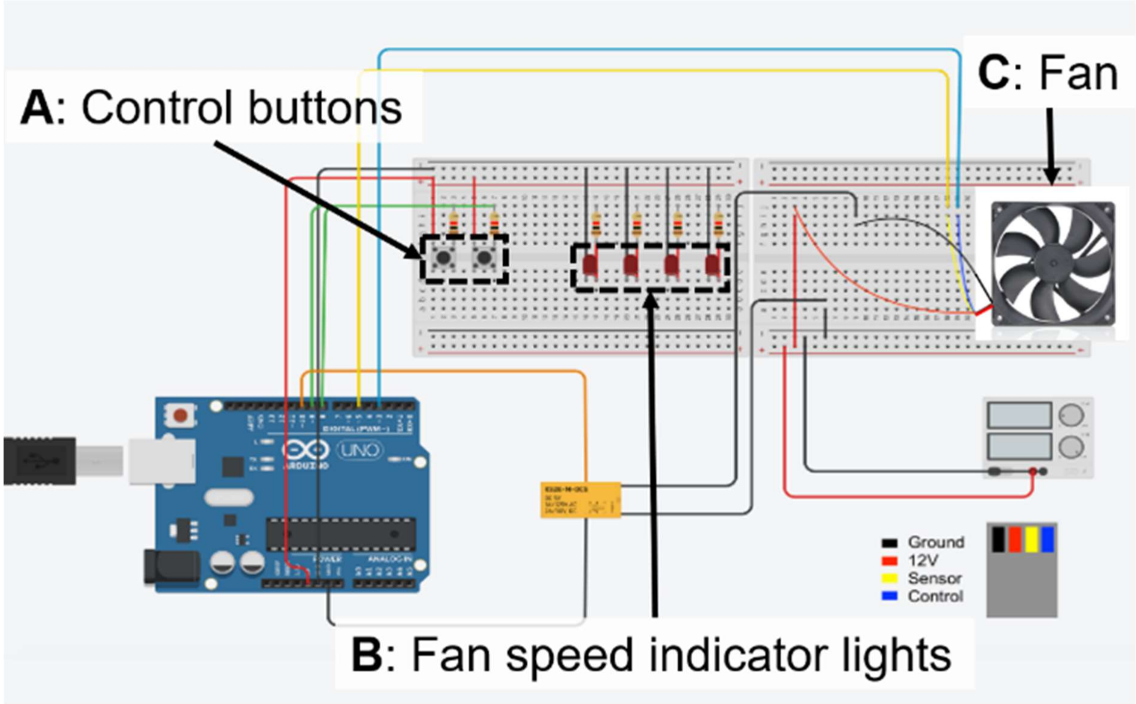


Figure 57: Circuit layout of testing application

The hardware and network were laid out as shown in Figure 58. The host laptop was connected to the Arduino via USB, and to the router via an Ethernet connection. The router was connected to the world wide web, through which it communicated with the remote client device.

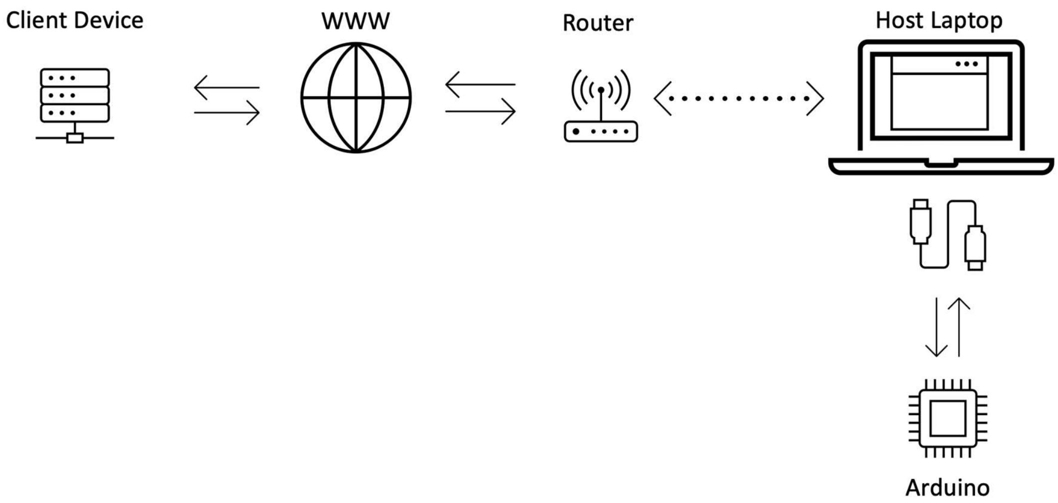
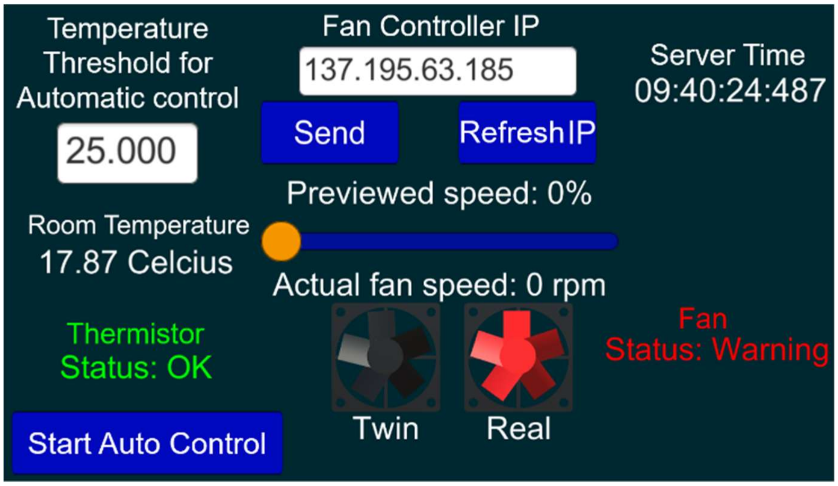


Figure 58: Hardware and network layout of testing application

The software application is shown in Figure 59. This is the interface as it appeared on a desktop PC, however visually identical interfaces were developed and deployed to Android, Mac OSX, Linux and HoloLens.


Temperature Threshold for Automatic control: 25.000

Fan Controller IP: 137.195.63.185

Server Time 09:40:24:487

Previewed speed: 0%

Room Temperature 17.87 Celcius

Actual fan speed: 0 rpm

Thermistor Status: OK

Fan Status: Warning

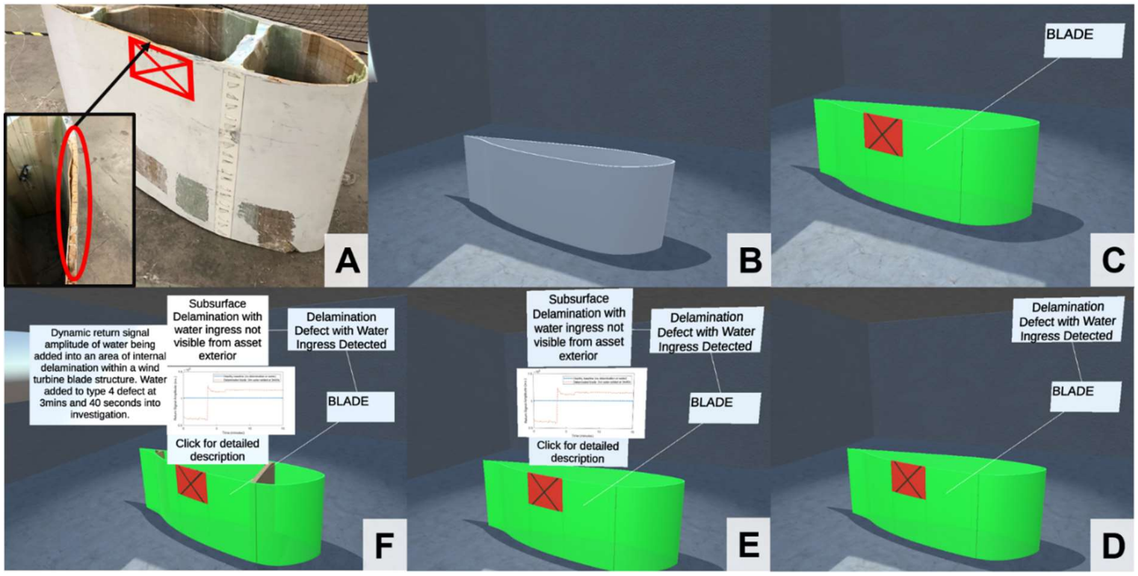
Figure 59: Software application for DT testing

Full manual and automatic control of fan speed were possible. Manual speed was determined by the slider. The speed change was previewed on the 3D model of the fan marked “Twin”. If the preview of the speed change was acceptable, the requested speed was then sent by clicking the “Send” button. The “Start Auto Control” button was used for automatic operation, which started and stopped the fan depending on whether the temperature threshold for automatic control was breached. If so, the fan turned on, if the room temperature was lower than the threshold, the fan turned off. The interface also contained voice control to start and stop the fan. The 3D model marked “Real” showed the rotation of the real fan. If the fan stopped rotating when it was supposed to be rotating, this model would highlight in red with a warning message displayed.

6.7 Asset Integrity Dashboard

Frequency Modulated Continuous Wave (FMCW) radar is a tool which can be used to determine subsurface defects in materials and composites [203]. The data it produces, however, is not human readable and must be interpreted into return signal graphs and other such visual means to be understood.

The Asset Integrity Dashboard (AID) tool shown in Figure 60 was developed as a concept of integrating FMCW data into actionable insights. This solves challenges faced by operators of wind turbines as it allows easy access of data about a blade in a synthetic environment. The tool allows a user to view increased tiers of technical complexity and level of detail on the severity of defects. The location of the defect is immediately obvious with the red colour coding and hatching pattern over the affected area. This data was collected by performing a raster scan on a decommissioned wind turbine blade section, shown in section A. Section B shows the digital representation of this blade, and C-F shows the various levels of detail on offer. The graph shown in sections E and F are the same as the one found in Figure 60. This simple application was developed as a proof-of-concept to enable further work in this area. The application takes no real time data and there is no real-time processing being performed. The intention of this work is to integrate it into the presented DT, to allow for fully automated offshore asset integrity inspections. This tool is available to use online at https://smartsystems.hw.ac.uk/prognostics-and-health-management-phm/.



Dynamic return signal amplitude of water being added into an area of internal delamination within a wind turbine blade structure. Water added to type 4 defect at 3mins and 40 seconds into investigation.

Figure 60: AID screenshots, showing the various levels of detail on offer.

A second application was developed, which featured an improved menu system, to view an adhesive thickness variation defect on a monolithic sample. The sample is shown in Figure 61.

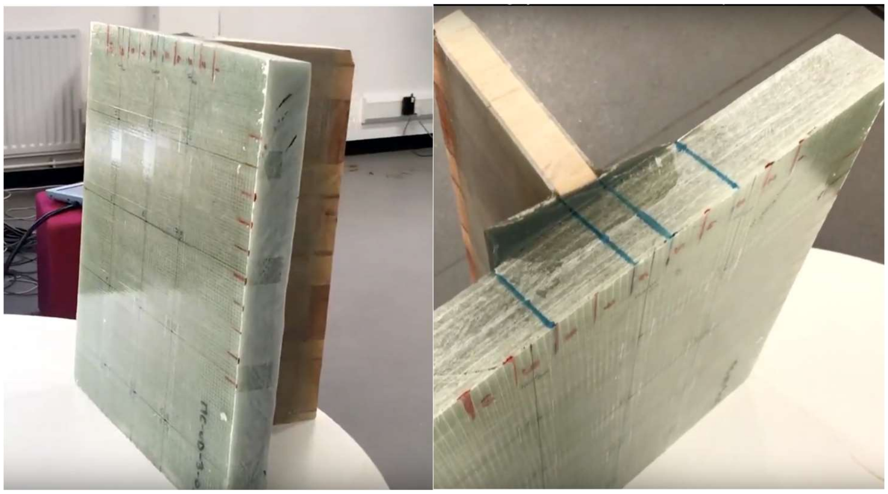
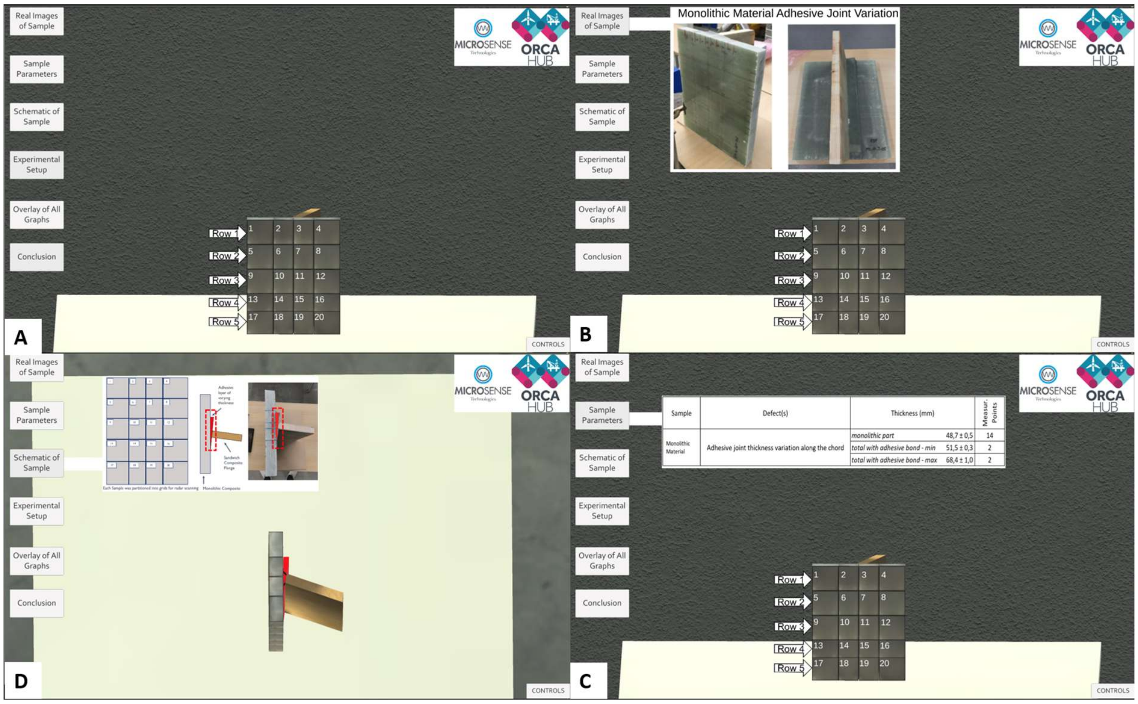


Figure 61: Monolithic material sample with visible adhesive thickness variation along the chord.

The purpose of the AID in its current, offline form is not to provide real time insight into the condition of an asset, UAV inspection is already available to perform surface level, visual inspections of remote assets and further examination is not possible until a reliable mounting method for the FMCW on these platforms is available. Instead, the purpose of AID is to provide visualisations which make sense of the raw data to an operator who is not a radar user but is familiar with the material science behind the turbine blades. Having this data in a remote application means the operator still does not need to be present when measurements are taking place. These visualisations are shown in the following figures.

Figure 62 shows basic informational overviews of the sample. The sample is gridded into 24 "bins", to align with the real sample. A is a full view of the sample, allowing the user to view a digital representation and rotate freely. B shows a comparison with real mages, with a brief overview description of the defect. C shows a top-down view detailing the location of the defect, highlighting it with a red hatching pattern and comparing to a provided schematic with the defect area. D shows measurements of the defect, with maximum and minimum adhesive thicknesses to demonstrate the variation in thickness.



Sample	Defect(s)	Thickness (mm)		Measur. Points
Monolithic Material	Adhesive joint thickness variation along the chord	*monolithic part*	48,7 ± 0,5	14
		total with adhesive bond - min	51,5 ± 0,3	2
		total with adhesive bond - max	68,4 ± 1,0	2

Figure 62: First 4 views of the AID tool for the monolithic sample showing basic information.

Figure 63 shows more detailed results including the FMCW return signal graphs. A shows the experimental setup for the data acquisition: a raster scan was performed from the top row, with bin 1 in the top left of the sample, to bin 4 in the top right, then down through the rows left to right. B shows the return signal from the FMCW, colour coded in the graph to indicate each row. To help with row identification, the digital representation of the sample is coloured to show the same scheme. C contains the same information, with return signals from a reference sample overlaid to highlight the baseline vs defected results. In this view, a photograph of the reference sample is included on the right of the screen. D is a depth map overlaid on the front of the sample, to show the thickness of the adhesive immediately. A white shading demonstrates a thicker adhesive, purple is zero adhesive. This version of the tool is available to use online at https://smartsystems.hw.ac.uk/asset-integrity-dashboard-version-2/.

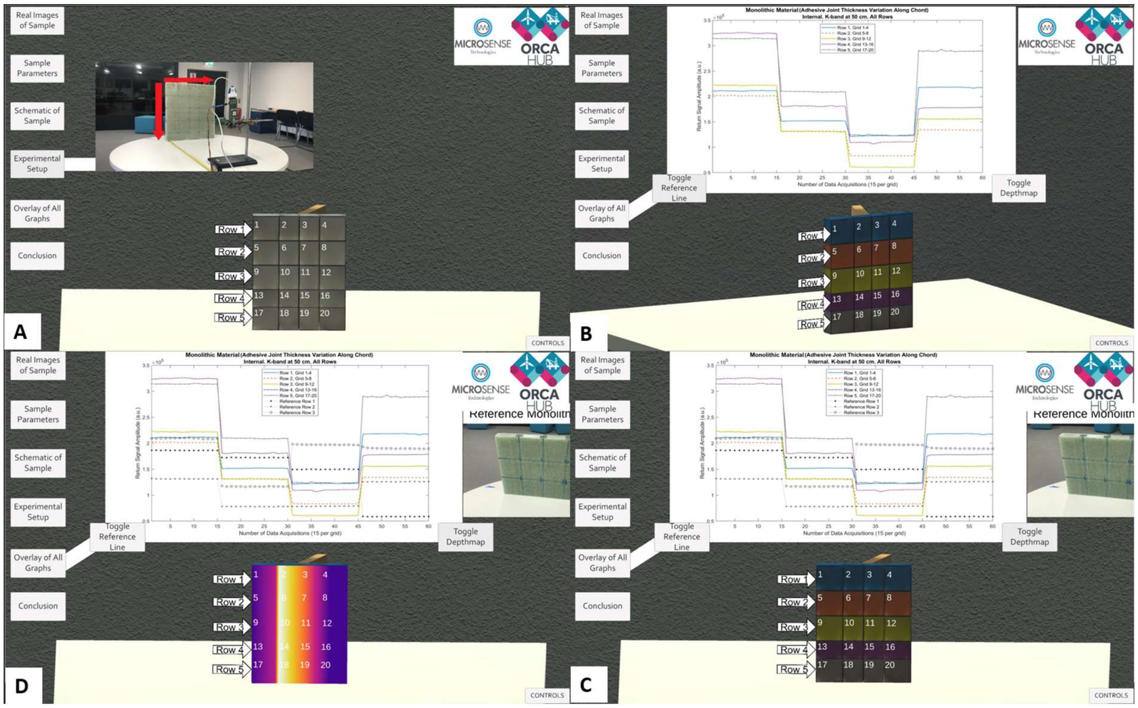
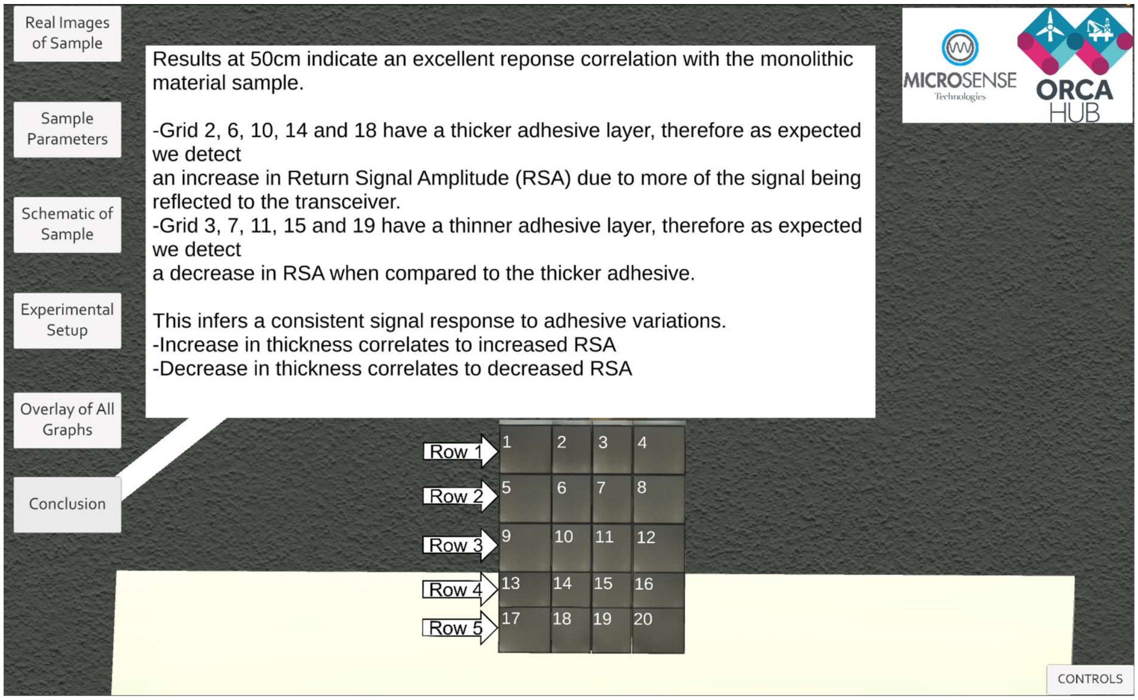


Figure 63: 4 views of the AID tool for the monolithic sample showing return signal data.

Finally, Figure 64 shows a detailed description of the sample and the findings of the raster scanning.



Results at 50cm indicate an excellent reponse correlation with the monolithic material sample.

-Grid 2, 6, 10, 14 and 18 have a thicker adhesive layer, therefore as expected we detect
an increase in Return Signal Amplitude (RSA) due to more of the signal being reflected to the transceiver.
-Grid 3, 7, 11, 15 and 19 have a thinner adhesive layer, therefore as expected we detect
a decrease in RSA when compared to the thicker adhesive.

This infers a consistent signal response to adhesive variations.
-Increase in thickness correlates to increased RSA
-Decrease in thickness correlates to decreased RSA

Figure 64: Description text in the AID tool for the monolithic sample.

Further work was carried out with the AID and the FMCW technology with EDF Renewables, including a site visit to Hartlepool in December 2021 to obtain more data on a full decommissioned wind turbine blade, shown in Figure 65. This visit involved using the Husky A200 robotic platform with dual UR-5 attachment to scan a section of blade and determine if it is possible to see subsurface defects within this blade. The results from the FMCW itself were found to be inconclusive, adverse weather conditions were suspected to be the cause but as the technology will need to be deployed offshore, such conditions are likely, and more development is required on the radar side to insure against this. The intent is to use a machine learning technique developed by Tang et al. to perform this analysis in run time, using the presented framework to handle data transfer mechanisms, to generate colour coding in the AID at run time [204]. The combination of this approach, with the resilient autonomy enabled by the DT presented in chapter 7, means automated asset integrity inspections should become possible.

Figure 65: EDF Renewables Hartlepool site visit, showcasing the full blade, the scanned section and the Husky platform performing a scan.

7 Operational Decision Support Interface

The Operational Decision Support Interface (ODSI) was developed to demonstrate the full realisation of CyPhER's potential in robotic DT applications. It addresses the identified gaps of symbiotic digital twins, which address the areas of digitalisation, operational decision support, human machine collaboration and edge computing, and proposed and implemented digital twins for the offshore renewable energy sector which address these areas. It was featured in an offshore robotics resilience demonstration in March 2022. The aim of this demonstrator is to showcase a SSOSA in action. It is proposed that through cooperation, collaboration and corroboration of different autonomous platforms, the chance of mission success is increased. This is seen as critical to meeting targets for offshore renewables, which necessitate the use of autonomous platforms to perform operation and maintenance procedures. The software is available at https://github.com/samharper94/ODSI.

7.1 Application Domain

The demonstrator aims to perform a routine asset integrity inspection in an offshore analogue environment, shown in Figure 66. All steps of the process are performed, including pre-mission planning, transiting to and performing scans, and returning to a pre-determined base point. The demonstrator is designed with failure modes in mind, with multiple points at which an autonomous platform will need to fail gracefully to preserve the mission, and ensure it is as successful as possible. This is enabled using other autonomous platforms, which have tasks to perform in the process, but can recognise and act upon a fault in another platform to ensure mission continuity.

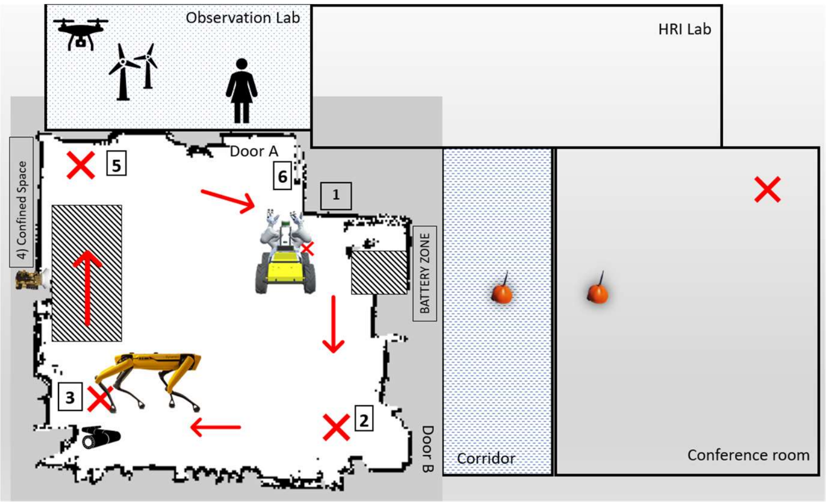


Figure 66: Layout of the resilience demonstrator, involving the Boston Dynamics Spot, Dual UR-5 Husky A200, DJI Tello and Limpet sensors.

7.2 Application Flow

The demonstrator will take the form of multiple pre-planned scenarios, an example of which is shown in Figure 67. The baseline mission, highlighted with a grey dotted line, stays the same throughout all scenarios. Resilience is demonstrated through the varying faults and failure modes which can be triggered on the robotic platforms, e.g. the Husky is unable to enter a confined space. These unplanned deviations are shown with the green dashed line. For the mission in the figure, the Husky platform will receive a low battery warning, which will cause Spot to transit to, manipulate and take a battery to Husky, and deposit the battery on Husky, allowing Husky to continue the mission. This scenario demonstrates resilience through the symbiotic relationship between the robotic platforms, interacting together to enable mission success.

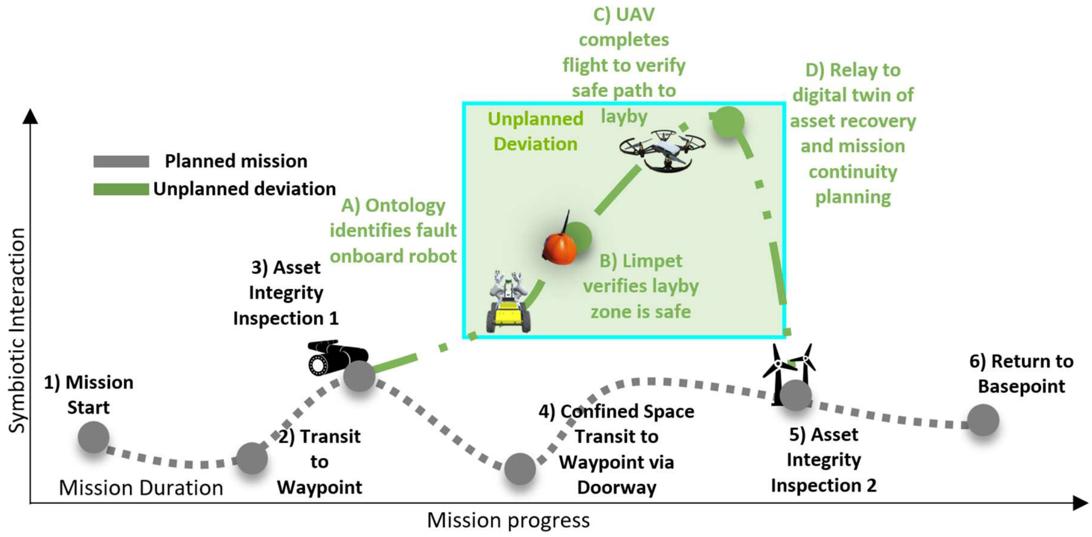


Figure 67: The scenario for the resilience demonstrator, showing corroboration and collaboration with different robotic platforms.

The ODSI is designed to use some ontology-informed thresholding to allow for autonomous decision making in a multi robot fleet. A diagram representing the flow of information in the application is available in Figure 49. The application flow for the resilience demonstration mission is shown in Figure 68.

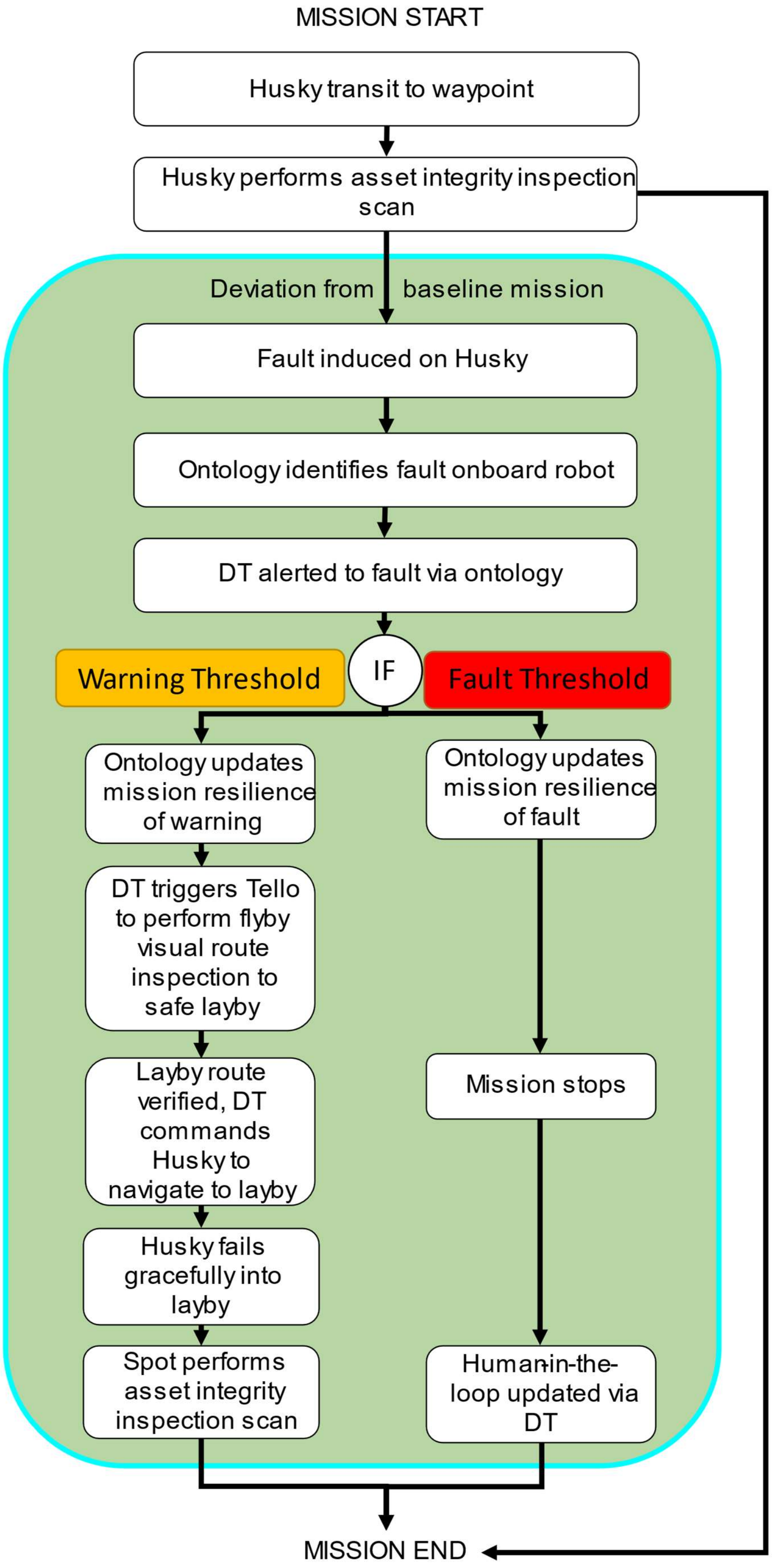


Figure 68: Flowchart of the mission plan for the resilience demonstration.

Additionally, the ODSI enables manual teleoperation of the DJI Tello drone. The flow for a custom flight plan using the Tello UAV is shown in Figure 69.

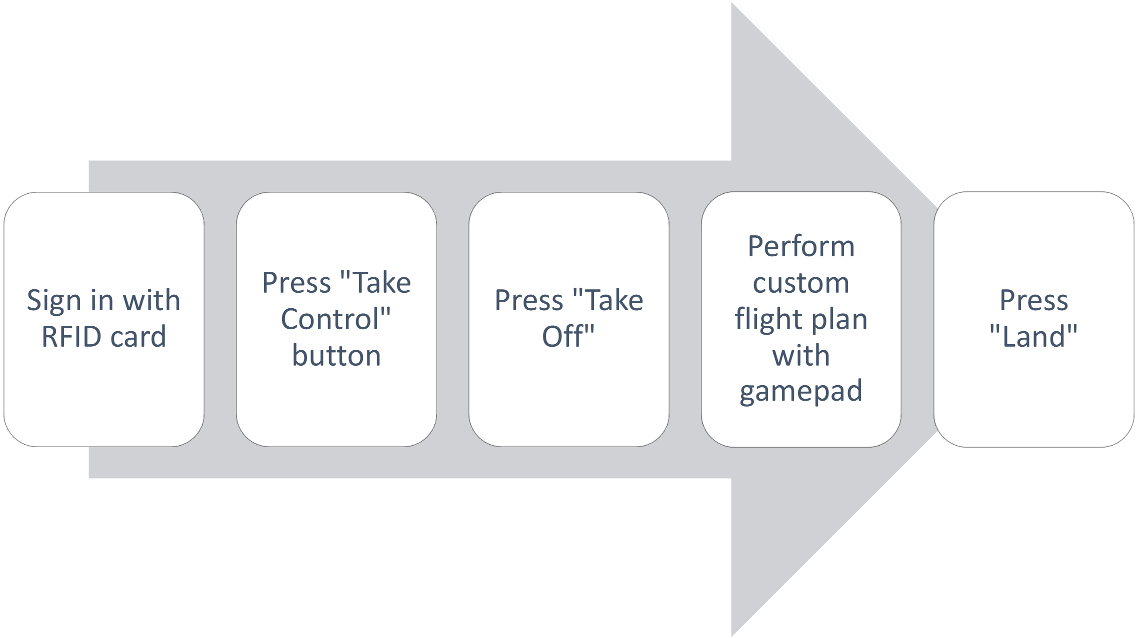
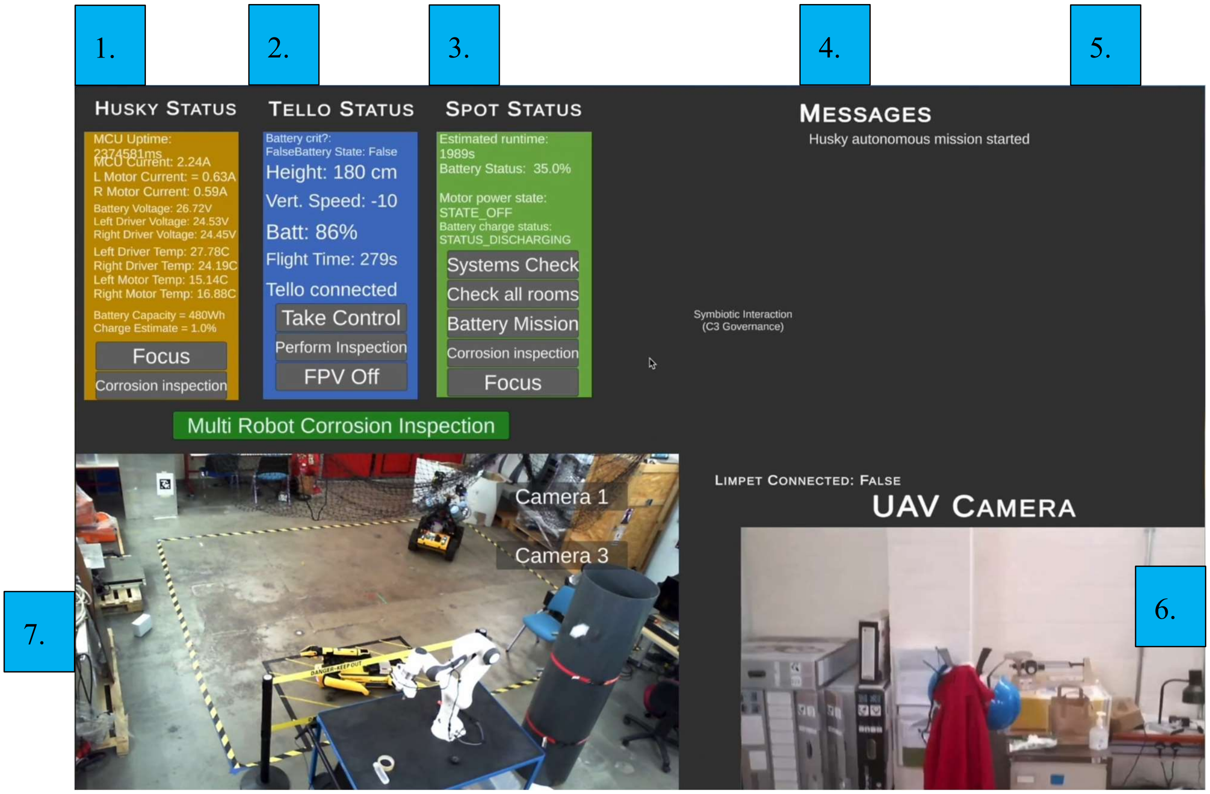


Figure 69: Flow of a Tello custom flight plan.

7.3 Application Implementation

The proposed ODSI layout is demonstrated in Figure 70. It was designed to show telemetry from three robotic platforms simultaneously, as well as some control options. The figure is annotated as below:

1. Status of the Dual-UR5 Husky A200 platform.
2. Status of the DJI Tello.
3. Status of the Spot.
4. Received messages from a connected device.
5. Teleoperation controls for the Tello with generated keyboard and gamepad control descriptions.
6. Camera feed from the DJI Tello.
7. Security camera interface with generated buttons to change between different cameras.



MCU Uptime: 2374581ms
MCU Current: 2.24A
L Motor Current: = 0.63A
R Motor Current: 0.59A
Battery Voltage: 26.72V
Left Driver Voltage: 24.53V
Right Driver Voltage: 24.45V
Left Driver Temp: 27.78C
Right Driver Temp: 24.19C
Left Motor Temp: 15.14C
Right Motor Temp: 16.88C
Battery Capacity = 480Wh
Charge Estimate = 1.0%

Battery crit?: FalseBattery State: False
Height: 180 cm
Vert. Speed: -10
Batt: 86%
Flight Time: 279s
Tello connected

Estimated runtime: 1989s
Battery Status: 35.0%
Motor power state: STATE_OFF
Battery charge status: STATUS_DISCHARGING

Husky autonomous mission started

LIMPET CONNECTED: FALSE

Figure 70: Annotated ODSI layout.

The interface is designed to allow the operator to take advantage of the connected hardware using one central interface. The network and hardware layout used for the ODSI is shown in Figure 71. This centralised design enables for the collaboration, corroboration, and cooperation of all connected hardware. It removes the need for using different clients for different devices, such as an Android handset for the Tello, Linux-based operating systems running ROS for Husky, or interfacing with Python scripts for Spot. The host laptop is connected to the RFID reader via USB and the DJI Tello via an exclusive WiFi connection (this is the only way of connecting to Tello). To enable communication with other devices and platforms, the laptop is connected to a router via Ethernet cable. This allows the laptop to connect to the internet, as well as every other device and platform used.

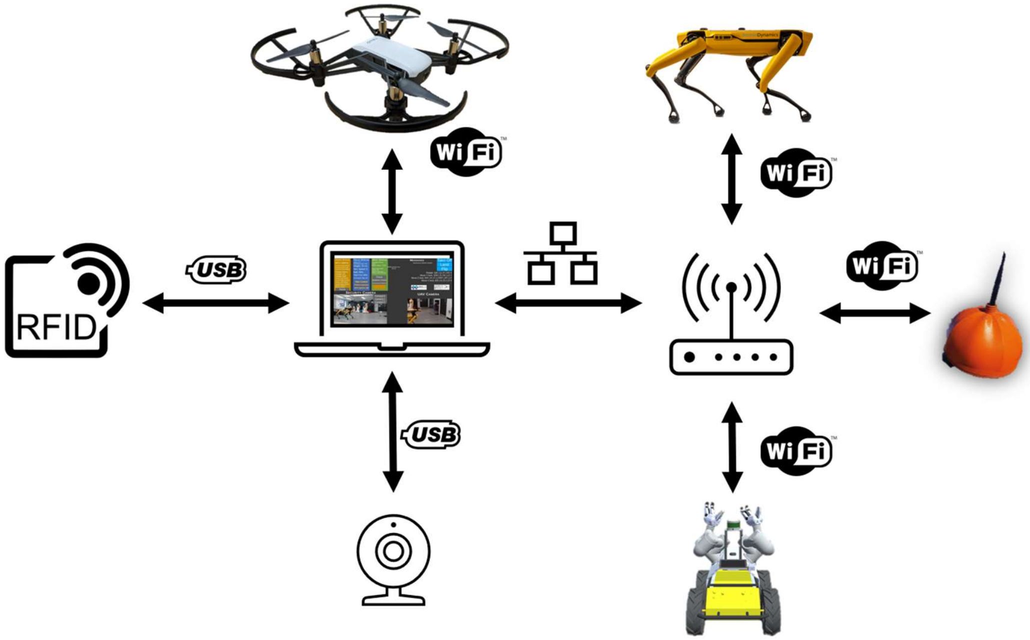


Figure 71: Network and hardware layout of DT Hub

Due to the use of Unity3D for development, the ODSI is also ready for use on lower powered Windows and Mac devices, due to the use of proprietary libraries for Tello operation, HoloLens and Linux support is not currently available. This approach of using the compute power available on each robotic platform means the ODSI needs to send a simple signal command to each platform to perform a task, as in the case of the Spot and Husky platforms the ODSI is used to perform actions which are pre-programmed into each platform. This lowers the compute burden on the DT itself.

7.4 Summary

The proposed DT is a critical aspect of resilient and symbiotic robotics. This case study was carried out to address the question if it was possible to provide a symbiotic, cyber-physical twin using the digital thread framework. It enables for run time control and telemetry of multiple, independent robotic platforms and enables them to collaborate, cooperate and corroborate to ensure mission success. It also enables human-systems symbiosis within offshore autonomous robotics. Extended reality is afforded through various interfaces dependent on the device and application in use.

This work has been published in part in 2020 IEEE Global Conference on Artificial Intelligence and Internet of Things [8], Offshore Technology Conference [9], IEEE Access (preprint) [1] and IEEE Energy and AI (preprint) [2]. Contribution to these works can be found in List of Publications at the start of this thesis. This work has also been demonstrated at KTN RAI 2021 [205] and as part of the 2019 ORE Catapult demonstration at Blyth [206]. This work has been featured on the Clearpath Robotics website [207], manufacturer of the Husky robot used within some of the applications. This work was also demonstrated at an industry-focussed offshore resilience demo in March 2022.

Whilst both frameworks are available to achieve different purposes, it is possible to compare ODSI to Gazebo in terms of the ability to run a DT. Differences in approach and capabilities are highlighted in Table 16.

Table 16: Comparison of ODSI and Gazebo

Capability	**ODSI**	**Gazebo**
Interoperable between robot manufacturers	✓	✓
API available	X	✓
Support for low powered devices	✓	X
Support for bandwidth constrained conditions	✓	X
Robot path planning visualisation	X	✓
Support for multiple operating systems	✓	X
Robot teleoperation	✓	✓

Future work in this area includes using AI and machine learning to characterise useful and non-necessary data for transmission. In bandwidth-limited situations, this will allow for reduced data transfer, and if a pattern can be identified, lower latencies in preparing packets.

8 CyPhER Metrics and Discussion

This chapter will discuss the evolution of the CyPhER framework throughout the case studies, a comparison with literature, and some performance metrics.

8.1 CyPhER Evolution through Case Studies

CyPhER evolved throughout the completed case studies. Each case study covered had differing requirements, necessitating the addition of new features to the framework. One-off analytics synchronisations with a central server were developed into continuous, run-time data transfer between multimodal sensors and devices, with agnosticism towards the data being transferred. These advances were afforded by more time invested into CyPhER's development, the improvement of extended reality and edge technology and more knowledge of comparable systems in different sectors. By using the application layout described in the reference architecture in Figure 20, CyPhER was able to be deployed to the diverse case studies included within this thesis. These case studies sufficiently justify and validate this framework as an initial major release at the time of this thesis, with future work on CyPhER to be carried out following thesis submission.

8.2 Comparison with Literature

Reviewing Table 7, the proposed digital thread framework enables the following:

- Extended Reality
    - Impact highlighted throughout.
- Digital Twins
    - Impact highlighted in 6 Implementation of CyPhER in Digital Twin Applications and 7 Operational Decision Support Interface.
- Interoperation with Hardware and Software
    - Impact highlighted in 7 Operational Decision Support Interface and 8.3 Portability of CyPhER Based Applications.
- Mixed Reality Vocational Education
    - Impact highlighted in 5 Implementation of CyPhER in a Virtual Learning Environment.
- Human-System Symbiosis

    - Impact highlighted in 4 Control-Display Gains, 6 Implementation of CyPhER in Digital Twin Applications and 7 Operational Decision Support Interface.
- Control-Display Gains
    - Impact highlighted in 4 Control-Display Gains and 5 Implementation of CyPhER in a Virtual Learning Environment.

In each area CyPhER was deployed, it allowed the capabilities of the developed application to exceed that of the compared applications from literature. Novelties were found in the use of extended reality especially, as this is still very much a developing field with prototype-level hardware.

8.3 Portability of CyPhER Based Applications

The software side of CyPhER was developed using .NET sockets in C#, however the techniques used can be ported to other languages with threading capabilities such as C++ and Python. The use of Unity3D for application development allows the applications to be deployed on a wide variety of digital platforms, including all major desktop OSs including Windows, Mac and Linux, as well as mobile platforms such as Android, iOS, UWP, HTML5 for web and current game consoles, needing only interface changes to account for the varying input methods. The data transmission component itself is designed to be “plug and play”, with the ability to toggle features on and off depending on application requirements and scale. This is opposed to the examples found in literature, which were built for one purpose only. A more detailed view of which platforms each application can be viewed in Table 17, with the year each application was developed in brackets.

Table 17: Platforms each application was deployed to.

Application	Windows	MacOS/OSX	Ubuntu	Android	Web	UWP
CD Gains (2018)	■	■	■	■	■	░
VET Application (2018)	░	■	■	■	■	░
Robotic Platform DT (2019)	░	░	■	■	■	░
Asset Integrity Dashboard (2020)	░	░	■	■	░	■
DT Testing Application (2020)	░	░	░	■	■	░
Digital Twin Hub (2021)	░	░	░	░	■	░

Key:
░ Implemented
■ Not implemented

8.4 CyPhER Numerical Metrics

This section will discuss numerical based metrics for framework performance. These show performance in terms of latency and memory usage. To prove out the capability of CyPhER with a DT, tests were performed whereby the fan setup described in Figure 57 was controlled via the following:

- HoloLens with a local WLAN connection to a MacBook Pro 17 connected to the apparatus via USB.
- Remotely on another area of the campus using the university’s Eduroam connection.
- Remotely completely off site in Edinburgh using WiFi, 3G and 4G.

The remote tests involved operating the fan with a video link. This allowed latency to be observed and visually identify any issues that presented over a greater distance and with different devices. These tests were used to prove the following:

- CyPhER can operate under local and remote communication environments.
- The capacity of CyPhER with respect to digital twins.
- The latencies induced by different wireless connection methods.
- The memory footprint of CyPhER.

8.4.1 Latency

The aim of the latency tests was to determine the performance of the DT over various wireless connection methodologies. To ascertain the added latency of using the Arduino, measurements were taken for identifying the latency between the server and the host laptop, as well as between the host laptop and the physical side. Data was sent from the server laptop to the client and back to the server to complete a roundtrip. The network topology was as demonstrated in Figure 58. To keep measurements consistent under different network conditions, the client was run on the Google Cloud Platform. To enable long-distance communications, the chosen datacentre was at the Google Data Centre in the USA. WiFi (router connected to optic fibre network), 4G and 3G were used as connection methodologies. 2G was considered but a handset capable of tethering and receiving a 2G signal was not available. Mobile networks were chosen to emulate the likely conditions of remote asset management, where a reliable ground internet connection may not be available. The speeds of each connection are shown in Table 18, higher is better.

Table 18: Speed of network connections

Network Connection	**Download Speed (Mbps)**	**Upload Speed (Mbps)**
WiFi (Hyperoptic)	162.82	133.81
4G (3 Mobile)	54.34	10.36
3G (3 Mobile)	26.20	3.45

The results of the network test are shown in Figure 72. The solid bar shows the latency of the data sent from the client to the user interface, and the hatched bar also includes the latency to the physical side (i.e., the fan turning on), accounting for the inherent latencies in the Arduino, with shorter bars showing less latency. The WiFi connection performed best, with the lowest latency at 30.8ms to the interface and 231.95ms to the physical side, showing a 201.15ms latency in the Arduino. An increase in latency is seen with the 4G connection, increasing to 105.17ms to the interface and 315.7ms to the physical side, showing a 210.53ms latency in the Arduino. 3G increases these latencies yet further, 128ms to the user interface, 338.81ms to the physical side, corresponding to a 210.81ms delay in the Arduino. Neither 2G nor 5G connections were available at the time of testing.

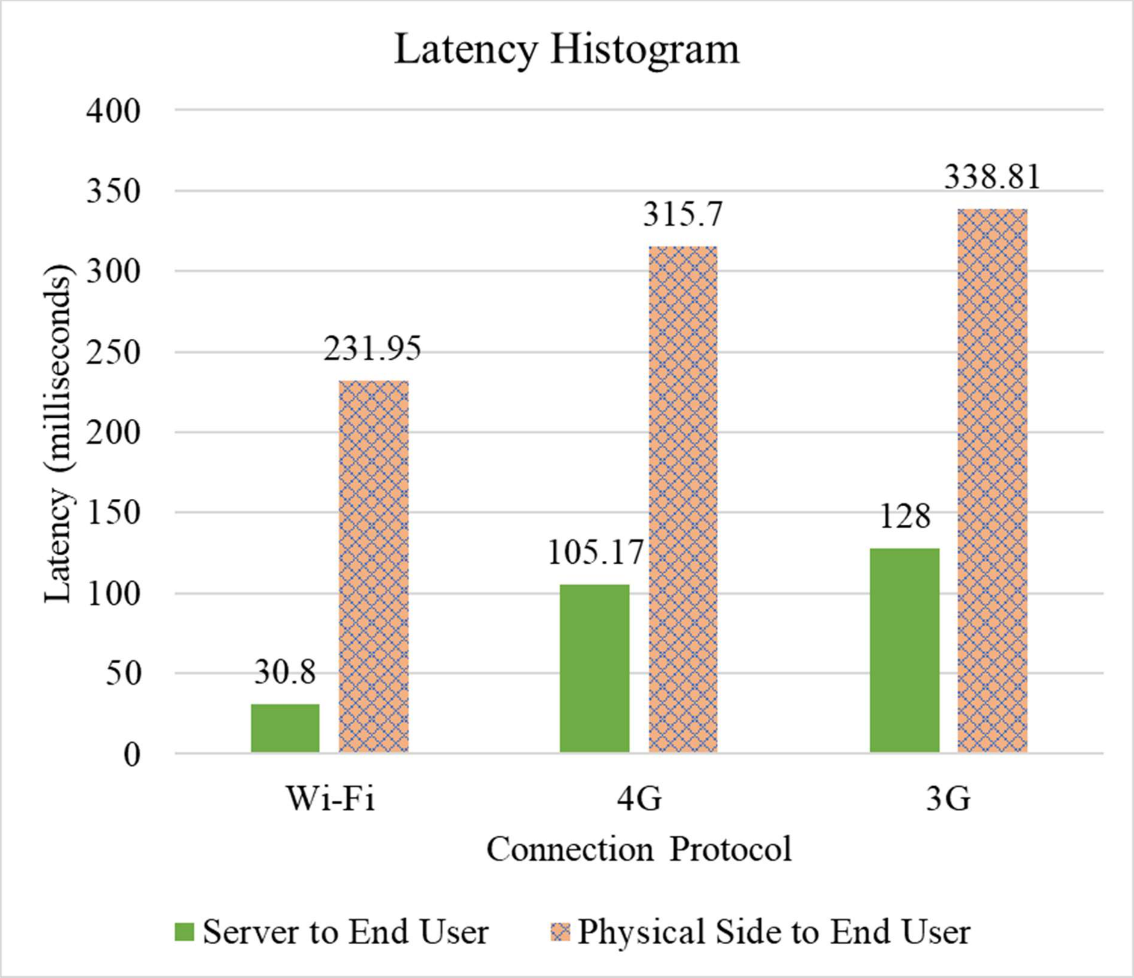


Figure 72: Latency histogram for each connection type. Latencies are from a MacBook Pro 17 to a remote server and back.

It has been proposed that an end-to-end latency of less than 300ms (lower is better) enables the user to feel as if they are in direct control, however latencies over this number are still acceptable for non-real-time operations (e.g., the data transfer in the VET application) [208]. Over WiFi, the full system exceeds this target, allowing the user to feel direct control over the system. Over 4G and 3G, this is not the case, and is instead categorised as “immediate” action, i.e., it is perceived by the user to be “easy to perform”. These increased latencies can be accounted for by using the Arduino platform, which from these tests added roughly 210ms delay onto every action. Therefore, a less latent middle system would reduce interaction latencies across the board, allowing all actions to feel instantaneous to the user, assuring them that they have a direct level of control over the system.

8.4.2 Thread Usage

To determine the maximum number of assets accepted by platforms with different numbers of available CPU threads, a test was carried out using a multi-threaded asset generator application. This application was used to emulate numbers of assets connecting to the server at the same time and sending data. The results of this test are shown in Table 19.

Table 19: Comparison of server machine performance

Device number from Table 14	**Device**	**Memory**	**Accepted number of assets**
1.	Desktop (Windows 10)	64GB	>1,800
2.	MacBook Pro 17 (OSX)	16GB	850
4.	Nvidia Jetson TX2 (Ubuntu)	8GB	500

The results of this test show the successful asset connections across a range of hardware from a large stationary workstation to the Nvidia Jetson edge computing device, all using different operating systems. The maximum number of simultaneous connections to device number 1 could not be evaluated due to the asset generation program running out of available threads to generate assets, so the maximum number of simultaneously connected assets is an undetermined number over 1,800.

8.4.3 Memory Usage

Memory usage changes per application, depending on what data is being sent. For ease of transferring between different applications, the data is always a string type encoded as bytes with ASCII. In .NET C#, this means that data usage will change depending on the length of the string. Byte size of a string message can be calculated using Equation (1).

$$\text{Byte size} = \text{string length} \times \text{bytes to encode one character} + 14 + \text{null terminator} \quad \textbf{(1)}$$

One character encoded as ASCII is 8 bits = 1 byte in length, and the null terminator is also 1 byte. Therefore, as an example, a small command string “a” from the DT Hub to a robotic platform to run “mission A” can be calculated as shown in Equation (2).

$$\text{Byte size} = 1 \times 1 + 1 = 2 \text{ bytes} \tag{2}$$

Whereas a longer telemetry message received from the Spot platform may read as the following: “1564 27.0 STATE_OFF STATUS_DISCHARGING”. Therefore, the message size can be calculated as shown in Equation (3).

$$\text{Byte size} = 38 \times 1 + 1 = 39 \text{ bytes} \tag{3}$$

Referring to the obtained download and upload speeds in Table 18, converting the slowest upload speed for 3G to bytes per second using the calculation in Equation (4).

$$\text{Bytes per second} = \frac{\text{Speed in Mbps}}{8} \times 1024^2$$
$$= \frac{3.45}{8} \times 1024^2$$
$$= 452{,}198 \text{ bytes per second (rounded down to remove partial byte)} \tag{4}$$

One TCP packet header has a size of 40 bytes. Therefore, maximum string length using ASCII encoding which can be sent in one packet over 3G can be calculated using Equation (5).

$$\text{Max. string length} = \frac{\text{Bandwidth} - \text{TCP Packet Header} - \text{null terminator}}{\text{Bytes to encode one character}}$$
$$= \frac{452{,}198 - 40 - 1}{1}$$
$$= 452{,}157 \text{ characters} \tag{5}$$

Alternatively, the greatest number of short strings which can be sent with individual packets can also be calculated using Equation (6).

$$\text{Max. strings} = \frac{\text{Bandwidth}}{\text{Shortest encoded string length} + \text{null terminator} + \text{TCP Packet Header}}$$
$$= \frac{452{,}198}{1 + 1 + 40}$$
$$= 10{,}766 \text{ individual single character strings} \tag{6}$$

Figure 73 plots the number of individual packets per second against the string length for this 3G connection.

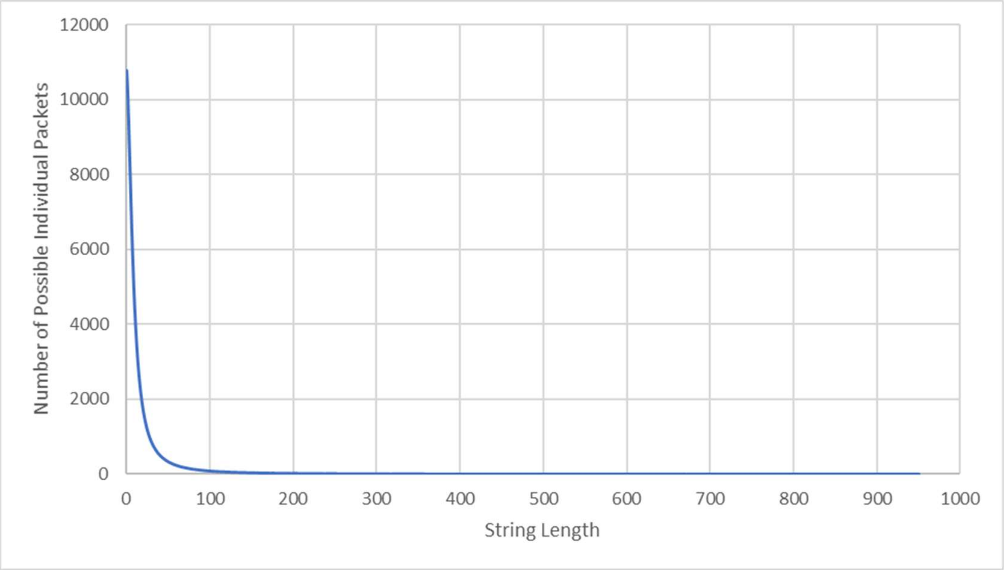


Figure 73: Number of possible individual packets per second vs string length for a 3G network connection.

This plot demonstrates a negative exponential trend as string length increases relative to the number of individual packets which can be sent. Therefore, it is important to consider the balance between many packets with little data and fewer packets with larger data, as a small difference in string length under 100 characters has a large effect on the number of individual packets, due to the TCP header overhead. When compared with the 1,800 reference number for the maximum connected assets, this means each asset can send strings which are 210 characters in length every second. Keeping the strings within one TCP packet also ensures the latency figures established in the previous section are preserved.

The number of bytes used to encode one character can change significantly depending on the encoding methodology used. ASCII only supports 128 characters, so especially for foreign language applications, or applications which rely on special characters, it may be desirable to use an alternative encoding method. For example, UTF-16 encoding has a fixed size of 2 bytes per character in a string, with a 2-byte null terminator, whereas UTF-8 has variable sizes depending on which alphabet is in use. Future work in this area may produce a more effective way of sending data tailored to each application, although this would reduce the generic property of this part of CyPhER.

8.5 Summary

This chapter evaluated CyPhER's metrics through its evolution, comparison to literature, portability, and numerical performance metrics. The evolution of CyPhER was borne out of necessity to adapt to the different case studies. CyPhER was deemed portable due to the wide range of devices that the framework and its applications were deployed to, in terms of computing capability and architecture.

For the performance metrics, the performance meets the expectations of such a system, and short discussions mention the current shortcomings of the approach and potential future improvements to these areas. The areas for numerical performance metrics were determined by their relevancy to the case studies covered in this work. Being able to perform in challenging network environments enables the use of CyPhER in the offshore scenarios encountered in the case studies, where connectivity is often poor. The high connected device limit enables comprehensive DTs of infrastructure, while the low latency allows for run time interactions with and monitoring of systems. The flexibility in message length allows for a system to be designed for long, infrequently communicated messages for non-time-critical use cases, e.g., submitting a long entry to a database after the conclusion of an activity, or short messages for high frequency communication, e.g., live telemetry from a robotic platform. It can be determined through CyPhER's performance and capabilities that it does address the gaps in knowledge highlighted in the literature review.

Retrospectively, the learnings gathered throughout the development of CyPhER could have altered the course of the earlier case studies if discovered before these studies were carried out. An example is the possibility of real time student monitoring from a remote platform for the VET application – using the data transfer knowledge acquired from the DT based applications it is possible to conceive using a similar system to send tool positions to a remote PC to allow a tutor to observe the student's processes.

9 Conclusion and Future Work

The proposed digital thread framework is a generic solution to enable symbiotic human-system interactions in extended reality cyber-physical twin systems. This thesis has presented a reference architecture and definition of CyPhER, along with supporting evidence to justify its novelty in the form of a literature review of existing and proposed systems and through case studies. CyPhER has attempted to address a research gap in a generic fashion by a modular approach to the framework design, to allow to be interoperable and adaptable in the platforms and applications it is used with.

9.1 Contributions of CyPhER

The case study applications themselves were novel for their fields, and were enabled by the underlying framework, which was enhanced as each study progressed. The completion and progression of these case studies opened new lines of research, which have been outlined in each study. Two of the case studies were developed for the field, provoked by industry, proving the maturity of CyPhER and its readiness to be distributed more widely. These works allowed the capabilities and transferability of CyPhER to be evaluated driven by real world use cases. Work from this thesis including this framework has been a part of peer reviewed and cited conference papers and journal articles, which further prove both its maturity and its novelty. Finally, the digital twin case study is being taken further, with a joint project with EDF regarding asset integrity inspection and a major resilience demonstration performed using the framework in 2022 [10]. Referring to Figure 4;

- CyPhER was found to present a generalisable digital thread framework that was suitable for multiple controls, workflows and human-systems applications.
- The cyber-physical twin reference architecture and techniques for interactions, data transfer and system integration were used to create case study applications across diverse fields with a standard architecture.
- The case studies performed received positive reception from personnel involved across vocational education and industrial robotics, enabling new interaction methodologies and opportunities for human-system interaction. These studies demonstrated how cyber-physical twinning can progress towards human-system symbiosis across fields.
- The case studies also served to improve CyPhER, with every study introducing new tools to the feature set and reinforcing the reference architecture used. These

improvements enabled CyPhER to be transferred more effectively between sectors, and operate on more diverse hardware as the studies developed.

The original hypothesis was as follows:

Human-system symbiosis can be enhanced by extended reality through a generalised digital thread framework that facilitates cyber-physical twinning.

It was found during the study presented herein that CyPhER does enable enhancement of human-system symbiosis. This was achieved through the consideration of human computer interaction through CD gains, using mixed reality to enhance learning experiences and using a DT to enable enhanced decision making. As CyPhER was developed, the question of machine-symbiosis was introduced through robotics which work together to achieve common goals. While this question was not fully explored in this work, its presence suggests some future work to be done in this area which can still be enabled by the principles of CyPhER; platform and device agnosticism, minimum resource use, bidirectional information exchange and synchronous data communications are as applicable to this field as they are to human-system interaction and are aspects which are required to enable machine-machine symbiosis.

However, the work presented herein did not fully create true human-machine symbiosis due to the limitations found during development. However, CyPhER does show that it enables the pathway to achieve this.

- For all work concerning MR interfaces, the release of the HoloLens 2 partway through development brought new interaction methodologies such as true 1:1 hand tracking which could not be tested in time.
- Some optimisation issues remained in the final versions of these applications as well due to developing knowledge in Unity for the 3D environments and scripting as time passed.
- For the VET application in particular, a large amount of time was spent developing the visuals optimising the cutting logic which would not necessarily be a factor for a developer experienced in Unity development and was not relevant to the performance and evaluation of CyPhER itself.
- In addition, the usability surveys were limited in their use due to the low number of participants available for evaluation. Whilst this was the full cohort available, if the

study was carried out in another country or field it would be possible to get more usability feedback.

- For the DT based applications, limitations were found in a lack of available hardware to fully stress the capabilities of CyPhER in terms of simultaneous connections, while this was evaluated through fake sensor generation this method may miss some factors presented when trying to connect 1800 tangible assets. It is possible this may present new challenges in terms of connection routing and wireless network saturation.

9.2 Potential for Further Development

The future use of CyPhER likely lies in the twinning of industrial robots and environments. Its application in the case studies presented is known, but as it is designed to be totally application agnostic it could be used for any cyber-physical system in future. It is a certainty that as new applications are introduced, new issues and shortcomings with CyPhER will become apparent, as they did over the course of this work. For this to be possible, the maintenance of CyPhER is important. While the framework itself is not available on GitHub as the conceptual features do not translate well to the platform, implementations with documentation are available at https://github.com/samharper94. Possible areas of future improvement are listed as follows.

9.2.1 Human-Systems Interaction Through CD Gains.

The results for these parts of the work may have been affected by the number of participants. Additionally, a limitation was found in terms of arm fatigue during the experimental procedure. Assigning the CD gains in a random order could assist in this regard, however, for future experiments it would be better to include a period of rest to allow the participants' arms to recover. Additionally, it was remarked a larger gesture frame would assist in this regard, this is provided by the HoloLens 2. While a test was not conducted with this device, the learnings from the original experiment can be taken over and re-evaluated on a more up-to-date device.

9.2.2 Performance of The Software Framework

Potential areas of improvement for the performance of this framework were highlighted in 8.4 CyPhER Numerical Metrics. These are particularly for memory footprint, number of threads and latencies. With more advanced techniques (e.g., using another encoding medium, more efficient messaging which can be characterised using machine learning to recognise useful and non-necessary data) it may be possible to reduce memory usage further. Likewise, latencies can be improved using more efficient data handling, or their effects minimised using CD gains to manipulate the user experience. This has the potential for its own research project for future inspection. The number of threads required could be reduced by using one thread for more than one connected asset, this would require some work in determining wait cycles to ensure the application would not hang while data is being processed from another asset.

9.2.3 Public Distribution

While the code base for CyPhER is maintained and thoroughly documented within the code, it is not yet ready for public distribution for multiple reasons. Data security has not been considered within this work; this is vital especially for enterprise implementations. An effort has been made to use open-source code where available, and for the developed software to be available with open-source licenses on platforms such as GitHub. However, proprietary projects in future may not be able to use some of the open-source licenses for third party works within Unity; Unity itself requires the purchase of an enterprise license when making for-profit applications. There is also the possible consideration of needing implementations in more programming languages than C# and Python. This is certainly possible but needs to be factored into the planning for any future project.

9.2.4 Cloud and Web-Based Systems

Consideration has been given to the possibility of using cloud and web-based services within this thesis. However, for a full cloud-based implementation, the network topology and framework implementation will need adjustments. The digital twin implementation can be thought of as running a local "cloud" system, with a centralised architecture, but its reliance on USB and local WiFi connections means this is impractical for cloud implementation in its current form.

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Appendix A: VET Questionnaires

A.1 BEACONING Questionnaire

Student Questions

1. What styles of games the students would want to play in a class (co-operative, competitive, quizzes, etc.)
2. Difficulty rating of the game.
3. Level of excitement generated by the game.
4. How much various aspects of gamification motivated them to carry out their tasks (leaderboards, progress bars, classroom comparisons, etc.).
5. How much various aspects of gamification would motivate them to carry out their tasks in STEM subjects
6. What feedback was expected from the game.

Teacher Questions

1. What components of a lesson plan need to be adjustable (difficulty, length, etc.)
2. How to tailor the lessons towards students with special needs
3. What data to consider for student assessment
4. If they think the students enjoyed playing the TVET game

A.2 SUS Questionnaire

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

SUS Scoring Formulae [209]

Questions are scored on a position from 1 to 5.

For odd-numbered questions:

$$Score\ contribution_{even} = Scale\ position - 1$$

For even-numbered questions:

$$Score\ contribution_{odd} = 5 - Scale\ position$$

Hence scaling all values from 0 – 4, with 4 being the most positive response. To achieve a score out of 100, the following is applied.

Overall score:

$$\frac{Overall\ Score}{100} = \sum Score\ contribution \times 2.5$$