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

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Abstract

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Keywords: Digital Twin, Extended reality, Inspection, Teleoperation, IoT

Contents

Table 1: Nomenclature

Abbreviation	Definition
AGV	Autonomous Ground Vehicles
AR	Augmented reality
ASV	Autonomous Surface Vessel
AUV	Autonomous Underwater Vehicles
AV	Augmented virtuality
BVLOS	Beyond Visual Line of Sight
C3	Cooperation, Collaboration and Corroboration
DT	Digital Twin
FMCW	Frequency Modulated Continuous Wave
HMDs	head-mounted displays
HRI	Human-Robot Interaction
IoT	Internet of Things
MAV	Micro Aerial Vehicle
MR	Mixed reality
O&M	Operation and Maintenance
ORE	Offshore Renewable Energy
PDDL	Planning Domain Definition Language
PLM	Product Life-cycle Management
RAI	Robotics and Artificial Intelligence
RE	Real environment
ROV	Remotely Operated Vehicle
RV	Reality-Virtuality
SDA	Symbiotic Digital Architecture
SSOSA	Symbiotic System Of Systems Approach
UAV	Unmanned Aerial Vehicles
VE	Virtual environment

1. Introduction

In various scenarios, human intervention is required to inspect critical infrastructures, such as offshore wind farms and [nuclear facilities[2]](https://www.semanticscholar.org/paper/Development-of-autonomous-working-robots-for-of-Wernke-Boser/f0037f51ee985507934dea9a4d21e96463f3b35d). These tasks can be dangerous and challenging for humans to perform, especially in hazardous environments or [hard-to-reach locations[9]](https://www.notion.so/https-www-youtube-com-watch-v-IlqcaNkjMRY-e18626d3e6a84f92ad17d07cdec82ed3?pvs=21).

The need for autonomous robots capable of executing missions with minimal human input is growing. These robots can help improve cost-efficiency and safety by reducing the reliance on human operators in challenging environments.

Implementing high-level decision-making capabilities in robots can help reduce costs associated with deploying human personnel and improve overall efficiency. Additionally, reducing the [cognitive load on human operators[1]](https://www.semanticscholar.org/paper/Towards-evaluating-the-impact-of-swarm-robotic-on-Paas-Coffey/4f49149507fae873f8b3192b8c78c14eafa4ceff) can enable them to control more robots simultaneously, further enhancing productivity. Using robots in conjunction with a digital twin, a robot with a lidar is well suited for a ****[Verification and Validation inspection](https://www.semanticscholar.org/paper/An-Overview-of-Verification-and-Validation-for-Fisher-Cardoso/5996e0e498d1aadc2fd85c3167e65f7084e1e56c)**** task. This report investigates how to [increase the level of autonomy autonomy, reducing human intervention](https://ieeexplore.ieee.org/document/6926394) through the use of AR in robotics.

In this study, a HoloLens-based solution was implemented using a digital twin of the robot and facilities. This approach allows for better visualization and control of the robot's actions in real-time, improving the overall effectiveness of the inspection process.

The implementation of the HoloLens-based solution and digital twin demonstrated promising results in improving the efficiency and safety of inspection tasks. The virtual environment facilitated better decision-making and reduced the cognitive load on human operators, enabling them to control more robots simultaneously[11].

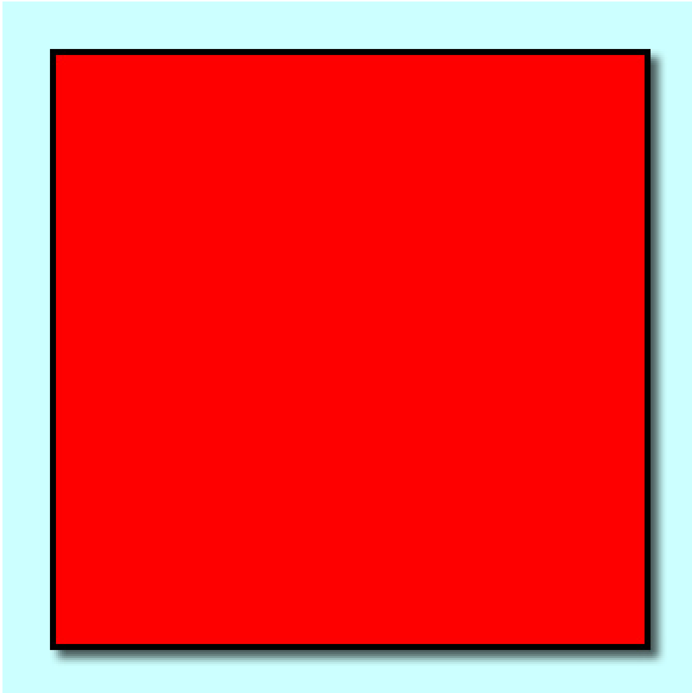

Figure 1: What I did. You can find a video [HERE] and a link to the project Github

2. Background

- Concepts:
  - Definitions
  - Digital Twin: A comprehensive description of the concept, its different forms, and its applications within the project.
  - Levels of Autonomy: An Explanation of the six Levels of autonomy and their relevance to the project.
  - virtuality, reality continuum.

2.1. *Digital Twin*

First introduced by Grieves in 2003 [11] in his presentation on product life-cycle management. Although this idea is not new, it remains a vague concept that encompasses a large variety of technologies and approaches. In general, a digital twin is a virtual representation of a physical asset or system that can be used to optimize and understand its physical counterpart. Communication can be bidirectional, where the physical asset is evaluated via sensors in real time and and digital twin can be simulated.

2.1.1. *Required components*

[14, 22] Without these components a digital twin cannot exist. These are:

- Physical Asset
- Digital Asset
- Information flow

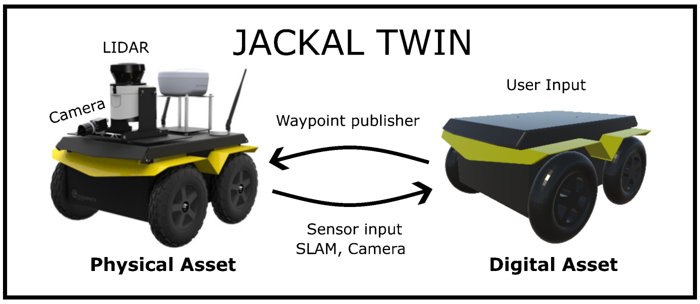

Figure 2: Physical Asset - Digital asset - Information Transfer

2.2. *Levels of Non-Intervention*

2.2.1. *Human Non-Intervention*

In the context of autonomous or collaborative robotics, human non-intervention refers to the reduction of human involvement in controlling or supervising tasks. With this in mind, the goal is to develop robotic systems that can operate independently or collaboratively with minimal human assistance. This allows for safer, more efficient operation in a number of applications such as **manufacturing, healthcare, and disaster response**.

2.3. *Levels of Autonomy*

The 6 Levels of autonomy[20] provide a framework to understand the level of involvement a human operator has in controlling a robotic system and develop the human intervention levels of robots [6]

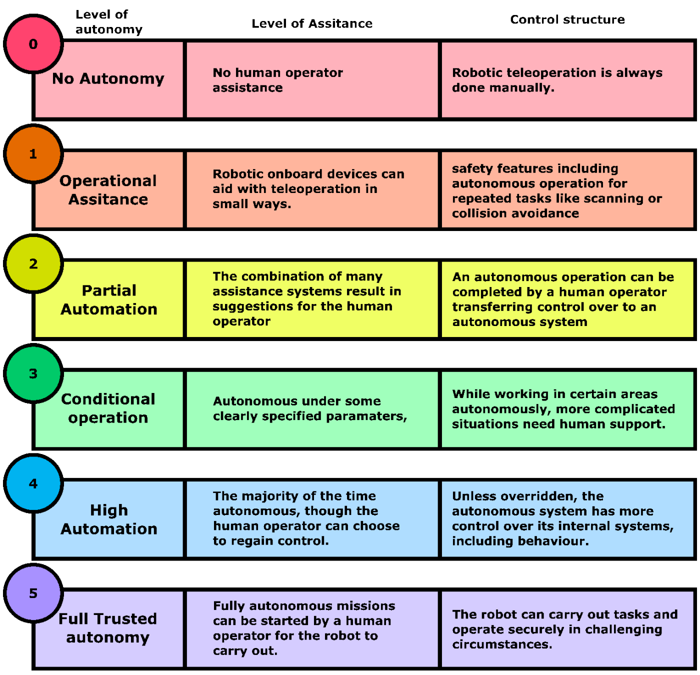

Figure 3: 6 Levels of autonomy

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

- Integrating Context using Artificial intelligence: [21]
- Reducing moral ambiguity:[3]
- Dimension-specific shared autonomy:[4]
- AI-driven robotics in surgery and autopsy:[17]
- Risky intervention and robotics challenges:[12]
- Brain computer interface for human-cobot interaction: [8]

2.4. *Reality-Virtuality (RV)* ***continuum***

Introduced in 1994[15], the RV continuum has been used as a framework for virtual and augmented reality development. This is a concept that describes different levels of immersion in virtual environments, which range from real world experience to completely virtual. With this, the three dimensions of the supporting taxonomy were introduced to describe the abilities of the visual display technology:

- extent of world knowledge
- reproduction fidelity
- Extent of presence metaphor

Reconsidering Milgram and Kishno's[23] theories in light of recent advancement since they were first introduced, we realise that the RV continuum is in fact discontinuous and that perfect virtual reality is not possible. Additionaly, mixed reality encompasses traditional virtual reality experiences and is actually more broad than previously thought. The updated taxonomy also includes coherence, which is crucial for evaluating contemporary mixed reality experiences, taking into account the role of users.

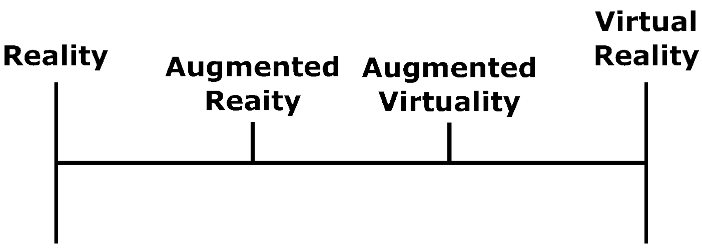

Figure 4: Virtuality, reality discontinuum

2.4.1. *Virtual, Augmented, and Mixed Reality*

Virtual Reality(VR): This is a computer-Generated simulation of an environment. This can be interacted with in a seemingly real or physical way by a person using specialised equipment.

Augmented Reality(AR): This is a type of display on the RV continuum that combines virtual objects with real word objects in real-time, creating a mixed reality experience. By overlaying digital information on the user's view this enhances the users perception of reality.

Mixed Reality(MR): Mixed reality is type of display on the RV continuum that combines real-world and virtual objects into and environment, allowing the user to interact with both[7]. This is a broader term that encompasses both AR and VR experiences.

2.5. *Cognitive load*

Cognitive load refers to the amount of mental effort required to complete a task. In the context of tele-operation, especially in challenging work environments[13], should not be overlooked. High cognitive load can degrade performance through increased errors, slower response times and narrowed focus, and fatigue, demonstrating the importance of designing human-robot interfaces that minimize unnecessary cognitive burden on operators. [9] The factors that influence cognitive load include:

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

3. Literature Review

3.1. *Factors affecting Digital Twin and XR techonlogies*

Using IEEE Xplore [1] a word search was conducted to find the main contributors to the growth of augmented reality used in conjunction with a digital twin to perform inspections. Figure 5 shows a steady growth in Inspection and Augmented realiy studies since 2006, increasing by 300%-400% in the last 16 years. Digital twin publications have increased by exponentially since 2016 with over 600 publications in this category per year.

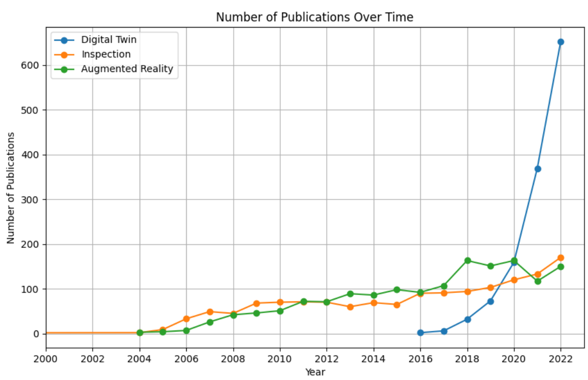

Figure 5: Publications per year

The most common phrases used in each category as well as word cloud representations can be found figures D.7,D.8,D.9,D.14,D.15,D.16 in the appendix.

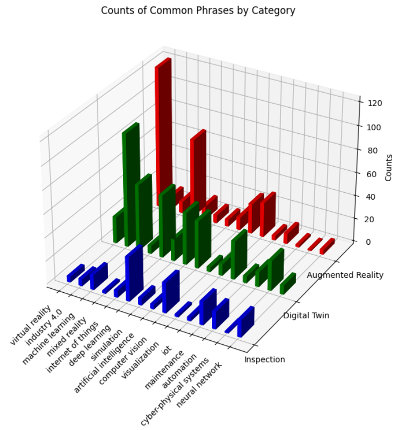

Figure 6: Most common phrases used by category

3.2. *Digital Twin Technology*

* Definition of digital twin * History of digital twins * Applications of digital twins * Benefits of digital twins * Challenges and limitations of digital twins

3.3. *AR and VR Technologies in Inspection*

* Overview of notable work in this area, such as "Teleoperation Using Google Glass and AR", "Drone for Structural Inspection", "Analysis of human-in-the-loop tele-operated maintenance inspection tasks using VR", "Using HoloLens to create a virtual operator station for mobile robots." * Discussion of the benefits of using AR and VR technologies for inspection, such as their ability to provide a more immersive and interactive experience, their ability to augment the user's vision, and their ability to provide access to remote locations. * Consideration of the challenges and limitations of using AR and VR technologies for inspection, such as their cost, their complexity, and their reliance on technology.

3.4. *Reinforcement of digital twin with VR and AR technologies*

* Discussion of how VR and AR technologies can be used to bolster the use and effectiveness of digital twins. * Example: How VR can be used to create a virtual environment that can be used to train inspectors on how to inspect a particular asset. * Example: How AR can be used to overlay digital information on the real world, such as the location of defects or the path that an inspector should take.

3.5. *Non-intervention frameworks for inspection, maintenance, and operation of facilities*

- Ultrasonic Imaging Technology: [18]
- Non-contact Sensing for Anomaly Detection in Wind Turbine Blades: [10]
- AR-supported Automated Environmental Anomaly Detection:[24]
- Autonomous Inspection System for Anomaly Detection in Natural Gas Pipelines: [19]

- Stochastic Cost-Benefit Framework for Maintenance Plans:[2]
- Smart Autonomous Maintenance in Industry 4.0:[16]
- Magnetic Crawler System for Autonomous Long-Range Inspection and Maintenance:[5]

4. Methodology

- Intended use:
  - Training: * How the solution aids in training users to manage high-level decisions. can be a simulated inspection. * Discussion of how the solution can be used to train users to make decisions in complex and dangerous environments.
  - Inspection of remote or dangerous locations: * Elaboration on the setup and operation of the solution in various environments. * Discussion of the benefits of using the solution in remote or dangerous locations, such as its ability to reduce the risk of injury to human inspectors.
- User interface - concept [DIAGRAM]:
  - Diagram of the user interface concept, showing the different components and how they interact.
  - Discussion of how the user interface concept can be used to provide users with the information they need to make informed decisions about the inspection.

5. Implementation

- HoloLens:
  - Detailed description of the implementation process using HoloLens.
  - Discussion of the benefits of using HoloLens for inspection, such as its ability to provide a mixed reality experience, its portability, and its ability to interact with the physical world.
- Jackal:
  - Explanation of the Jackal's role in the solution and its interaction with the HoloLens and digital twin.
  - Discussion of the benefits of using Jackal for inspection, such as its ability to navigate autonomously, its ability to carry a payload, and its ruggedness.
- SLAM (Simultaneous Localization and Mapping):
  - Explanation of the SLAM's role in the solution, particularly in detecting new objects.
  - Discussion of the benefits of using SLAM for inspection, such as its ability to create a map of the environment and its ability to track the robot's position.
- Actual user interface [DIAGRAM]:
  - Diagram of the user interface, showing the different components and how they interact.
  - Discussion of the benefits of the user interface, such as its ease of use and its ability to provide the user with real-time information about the inspection.

6. Results

- Detailed description of the primary results or findings of the project, including any statistical analysis or other data-driven insights. * Example: The system was able to detect and classify defects with an accuracy of 95* Example: The system was able to complete an inspection in half the time it would take a human inspector.
- Discussion of any challenges or problems encountered during implementation. * Example: The system was not able to detect defects in certain types of materials. * Example: The system was not able to navigate in complex environments.
- Comparison between the performance of the proposed system to traditional inspection methods, including a discussion of the benefits and limitations of each approach. * Example: The proposed system is more accurate than traditional inspection methods. * Example: The proposed system is more efficient than traditional inspection methods.

7. test

8. Conclusion

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

The key achievements of the project include:

* The development of a novel system that combines the benefits of digital twins, AR, and VR. * The successful implementation of the system in a real-world setting. * The demonstration of the effectiveness of the system in terms of cost, safety, and efficiency.

The primary benefits of the system include:

* Increased safety: The system can reduce the risk of injury to human inspectors. * Increased efficiency: The system can reduce the time and cost of inspections. * Increased accuracy: The system can improve the accuracy of inspections.

9. Future Work

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

* The development of a more sophisticated digital twin that can better capture the physical properties of the asset being inspected. * The development of a more immersive AR experience that can provide inspectors with a more realistic view of the asset being inspected. * The development of a more robust VR training environment that can be used to train inspectors on how to inspect different types of assets. * The adaptation of the system to other applications or environments, such as the inspection of buildings or the inspection of pipelines.

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10. Appendix

Appendix A. Diagram of the user interface concept

[Diagram of the user interface concept]

Appendix B. Map of the inspection environment

[Map of the inspection environment]

Appendix C. Video of the system in operation

[Video of the system in operation]

Appendix D. word search

Appendix D.1. Top phrases per topic

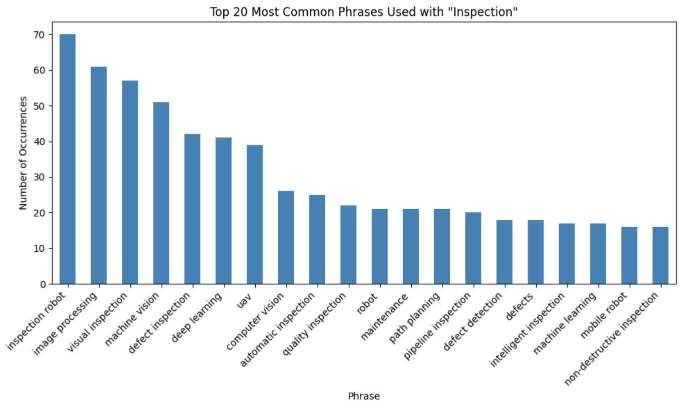

Figure D.7: Top phrases associated with the topic ”Inspection”

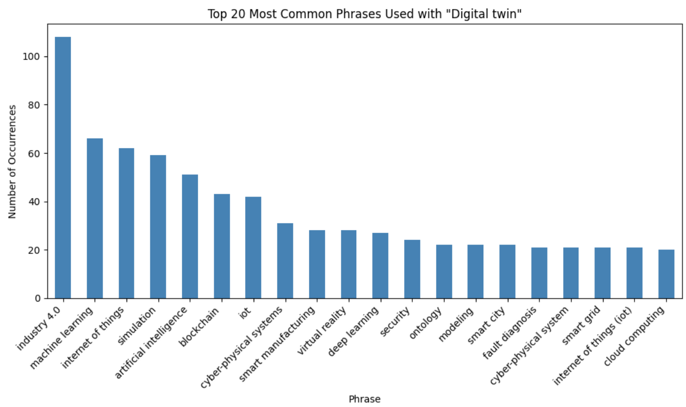

Figure D.8: Top phrases associated with the topic ”Digital Twin”

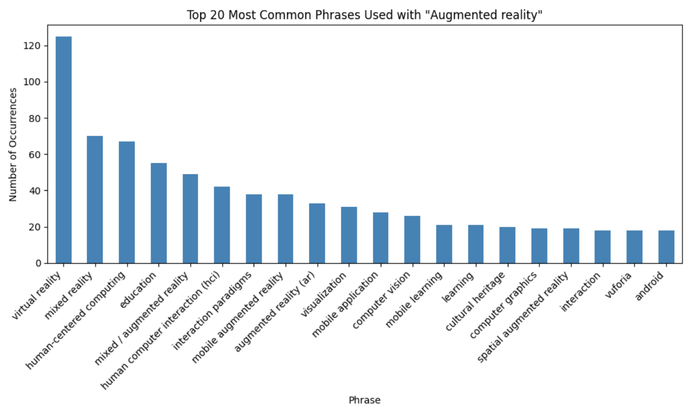

Figure D.9: Top phrases associated with the topic ”Augmented Reality”

Appendix D.2. Top common phrases per topic

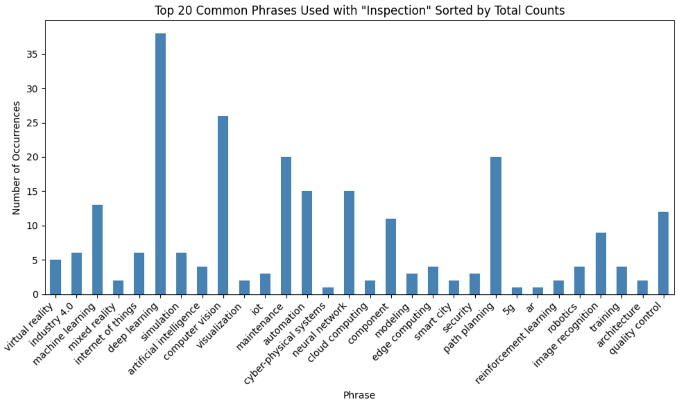

Figure D.10: Most common phrases used in the ”Inspection” topic

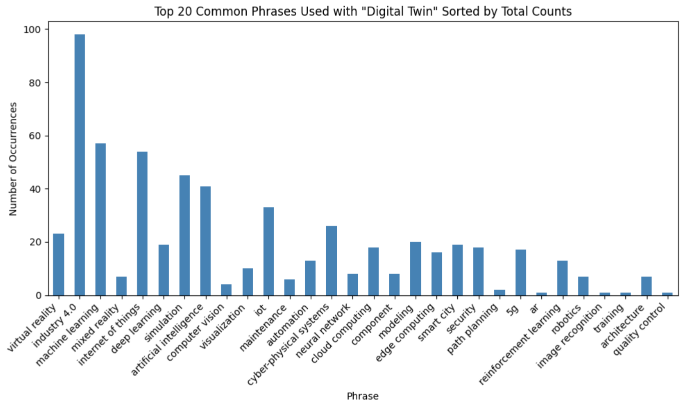

Figure D.11: Most common phrases used in the ”Digital Twin” topic

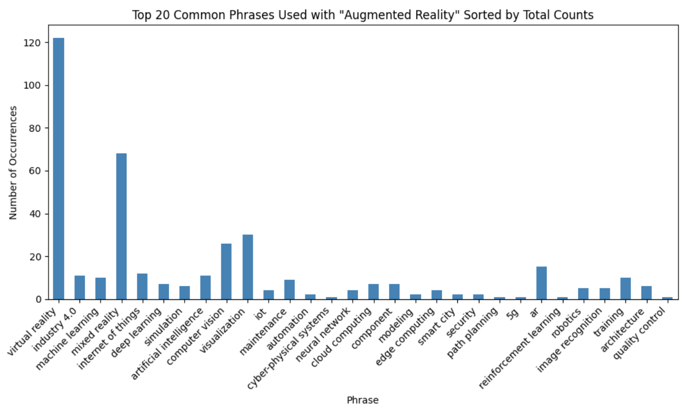

Figure D.12: Most common phrases used in the ”Augmented Reality” topic

Appendix D.3. Word-clouds

Appendix D.3.1. Word-cloud of common words

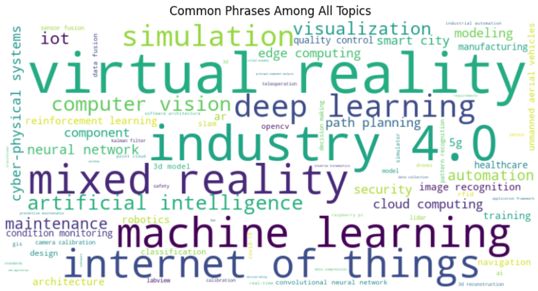

Figure D.13: Phrases commonly used in all categories

Appendix D.3.2. Word-clouds by category

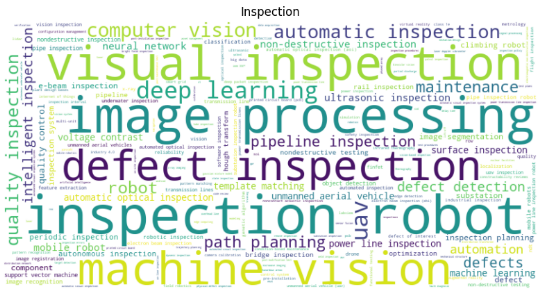

Figure D.14: Phrases commonly used in the "Inspection" topic

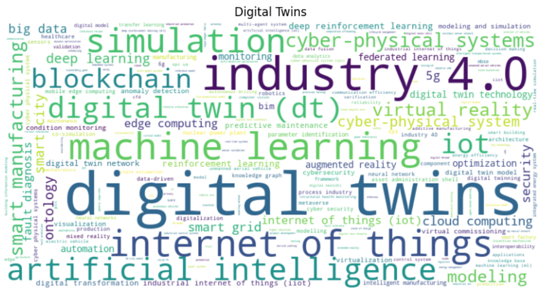

Figure D.15: Phrases commonly used in the "Digital Twin" topic

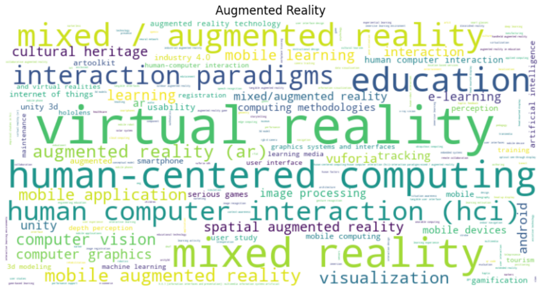

Figure D.16: Phrases commonly used in the "Augmented Reality" topic