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Master's Thesis

Mixed Reality Environment for Robot-in-the-Loop-Testing using Digital Twins

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Abstract

Hier sollte in einem Abstract kurz der Inhalt der Arbeit erläutert werden. Zuerst auf deutsch.

Then an abstract of the thesis in english should follow.

Contents

1 Introduction

Robotic and Autonomous Systems (RAS) combine multiple disciplines, including control engineering and robotics, mechanical engineering, electronics, and software engineering. Testing these systems is not as straightforward as using traditional methods and they require more because they span multiple disciplines. For researchers and engineers specializing in software testing, adapting existing techniques for RAS presents a significant challenge. This is why there is extensive literature dedicated to proposing and evaluating different testing techniques and processes, showing how esential it is to establish structured methods for ensuring the reliability of these complex systems. [AMV23]

This validation challenge highlights a fundamental tension between simulation-only testing and full-scale physical experimentation, which are the two established methods in robotics evaluation. Simulation is central to the robotic development, offering a way to test control logic and experiment with system configurations before committing them to hardware [Hu05; Mic04]. Simulations are often easier to set up, less expensive, and can run faster than real-world tests, allowing for rapid design exploration and to get better grasp of complex algorithms [Mic04; DRC+17; BM18]. However, a gap between the virtual and physical worlds emerges when simulation models are abandoned during the implementation phase. Virtual models, by their nature, cannot perfectly represent every characteristic of a physical hardware, such as the exact effects of friction, sensor noise, or small differences in motors [Hu05; BM18]. On the other hand, testing with real hardware provides the highest fidelity and allows for controls to be refined based on presence of all the unpredictable physics and variability, that simulations can't replicate [Hu05; CCC+21]. But this approach has its own severe drawbacks. Conducting physical experiments can be resource-intensive and time-consuming and requires significant funds, manpower, and infrastructure [Hu05; DRC+17; Mic04]. Furthermore, some critical scenarios, such as emergencies, are too dangerous to be recreated in the physical world [Hu05]. For complex, large cooperative systems, testing the entire system with only real components may not even be feasible due to the issues of complexity and scale [Hu05]. Since neither approach on its own is sufficient, there

is a need for an intermediate solution that can connect the simulation with real-world experimentation [Hu05].

To bridge this validation gap, hybrid paradigms such as Hardware-in-the-Loop-Simulation (HILS) have emerged, in which parts of a pure simulation are replaced with actual physical components [Hu05]. This research focuses on a specific application of this concept known as "robot-in-the-loop" (RitL) simulation, a novel method that allows real robots and robot models to work together for system-wide measurement and test [Hu05]. This paradigm provides the flexibility to experiment with real robots in a virtual environment, allowing them to be tested and evaluated even when a full physical environment is not available [Hu05]. This hybrid interaction is enabled by a core enabling technology: the Digital Twin [AA23]. A digital twin is a virtual copy of the physical thing that can monitor it in real time [AA23]. Through connectivity and rapid processing, the digital twin is able to mirror the physical asset and synchronize data with it [AA23]. To manage this complex hybrid test environment, Augmented Reality (AR) is increasingly utilized as a new medium for interaction and information exchange with autonomous systems, enhancing the efficiency of Human-Robot Interaction (HRI) [MV20]. The powerful combination of RitL testing [Hu05], synchronized Digital Twins [AA23], and intuitive AR interfaces [MV20] represents a state-of-the-art approach for developing and validating the next generation of complex robotic systems.

A system that integrates these concepts of digital twins, augmented reality (AR), and vehicle-in-the-loop testing is the "Virtual Environment for mobile Robotic Applications" (VERA) framework, which was designed to bridge the gap between simulation and real-world testing [Geh24]. VERA provides a modular platform for creating, managing, and visualizing synchronized virtual environments, which are presented both in simulations and as real-world projections [Geh24]. This master's thesis builds directly upon the foundation laid by this original framework.

While the VERA framework provided a promising conceptual foundation, its original implementation has several documented limitations that this thesis seeks to address [Geh24]. A primary limitation was that its custom environment manager could not offer a full physics simulation, with the integration of enhanced physics noted as a direction for future work [Geh24]. Furthermore, the 2D visualizer, based on Pygame, encountered performance degradation when handling a high number of dynamic objects; in scenarios with many updates, its capacity was exceeded, leading to delayed and incomplete visualizations [Geh24]. Lastly, while AR-like projections were implemented, more immersive Virtual Reality (VR) interaction was not part of the original scope and was identified as a potential future extension [Geh24]. Therefore, the central problem is that the original VERA framework, while conceptually promising, is techni-

cally constrained by its custom components, limiting its physical realism, performance scalability, and interaction capabilities.

To address these technical constraints, the primary objective of this thesis is to replace the custom simulation and visualization components of the VERA framework [Geh24] with the Unity Engine [Uni23]. This implementation will leverage the Unity Engine [Uni23], which was selected specifically for its advanced graphics, integrated physics, and native VR support, to overcome the previously identified constraints of the VERA system.

The core goal is to establish a high-fidelity, real-time digital twin [AA23] of the EMAROS robot [Geh24], incorporating not only its model but also its live sensor data and physical properties, such as mass, inertia, and collision models. This digital twin will serve as the foundation for "robot-in-the-loop" [Hu05] testing scenarios. Furthermore, this project will implement user interaction, moving beyond the original AR projections [Geh24] to include Virtual Reality (VR) [EM21] and desktop interfaces for scenario modification, robot control, and data visualization. This also includes reimplementing and enhancing VERA's AR floor projection feature by utilizing Unity's advanced rendering tools to improve visual quality and system capabilities [Uni23].

[**NOT FINAL**]The remainder of this thesis is structured as follows: Chapter 2 reviews the foundational concepts of Robot-in-the-Loop testing, Digital Twins, and Mixed Reality, and includes a detailed review of the original VERA framework. Chapter 3 defines the new system requirements based on VERA's limitations. Chapter 4 details the implementation of the new architecture, including the Unity/ROS 2 integration, the EMAROS digital twin and the implemented scenarios. Chapter 5 presents the evaluation and discusses the results. Finally, Chapter 6 summarizes the thesis contributions and provides an outlook on future research.[**NOT FINAL**]

2 Background and Related Work

This chapter provides an overview of the foundational concepts and related work that underpin the development of a Mixed Reality Environment for Robot-in-the-Loop Testing. Each section discusses key principles, methodologies, and existing implementations relevant to the thesis.

2.1 Robot-in-the-Loop-Testing

The validation and verification of modern Robotic and Autonomous Systems (RAS) is a significant challenge due to their inherent complexity [AMV23]. This complexity arises from integrating many different fields, including software, mechanical, and electrical engineering [AMV23]. A central difficulty is testing the connection between the system's software and its hardware aspects at the same time [AMV23]. To address this, the "X-in-the-Loop" (XitL) simulation paradigm acts as a crucial bridge, connecting the flexibility of pure software simulation with the high fidelity of full-scale physical testing [Bra+19].

A foundational XitL method is Hardware-in-the-Loop (HIL) simulation, which is a critical technique for testing complex mechatronic products [Mih+22; Bra+19]. The main principle of HIL is creating a closed loop between the real hardware being tested and a real-time computer simulation that represents the rest of the system or its operational environment [Mih+22]. This setup effectively tricks the hardware into behaving as if it were operating in the complete, real system, allowing for thorough testing across a wide range of virtual scenarios [Bra+19]. The primary reason for using HIL is to shorten development cycles and prevent costly or dangerous failures by making exhaustive testing possible before the system is deployed on the actual physical "plant" [Mih+22]. Because of this, HIL is essential in safety-critical industries like automotive, aerospace, and robotics, where real-world testing can be too expensive, dangerous, or even impossible [Bra+19].

Building on the HIL concept, Robot-in-the-Loop (RitL) simulation is a specialized paradigm where the hardware under test is a complete robotic system, such as an

uncrewed vehicle [Mih+22]. RitL is directly related to HIL, replacing parts of a pure simulation with the physical robot to increase the test's fidelity [Hu05]. As illustrated in Figure **??**, a typical RitL configuration has the robot's real actuators operating in the physical world while its perception is fed by a simulated virtual environment [Hu05; Mih+22]. This creates a hybrid reality where, for instance, the robot might use "virtual sensors" to see objects in the simulation while using its real motors as HIL actuators to move physically [Hu05]. To keep the physical and virtual worlds synchronized, the real robot often has a "virtual counterpart" in the simulation whose state is updated as the physical robot moves and acts [Hu05].

Figure 2.1: Conceptual diagram of a Robot-in-the-Loop (RitL) simulation, showing the real robot interacting with a virtual environment. The real robot's actions affect its virtual counterpart, and the virtual environment provides sensor data back to the real robot.

The main benefit of RitL is the ability to conduct repeatable testing of high-level software, like navigation algorithms, using the dynamics of real hardware [Mih+22]. This avoids the cost, complexity, and danger of a full physical testbed [Mih+22]. RitL is therefore invaluable for safely validating system performance in a lab. This is especially important for safety-critical applications or for testing in environments that are hard to replicate, such as a Mars rover mission or a large-scale robot swarm [Hu05; Mih+22].

The RitL paradigm has been widely applied to validate complex autonomous systems, especially in the automotive industry through Vehicle-in-the-Loop (VitL) testing. The "Dynamic Vehicle-in-the-Loop" (DynViL) architecture, for instance, integrates a real test vehicle with the high-fidelity CARLA simulator, which is built on the Unreal Engine [DSR+22]. As shown in Figure **??**, this approach allows a physical vehicle on an empty track to be stimulated by sensor data from a complex virtual world [DSR+22]. This enables the safe and repeatable testing of automated driving functions in scenarios that would be dangerous to replicate physically [DSR+22]. A similar "Vehicle-in-Virtual-Environment" (VVE) method also uses CARLA and the Unreal Engine to create a closed loop where the real vehicle's motion is tracked and reflected in the virtual world, allowing its control systems to react to simulated events [Cao+23].

Figure 2.2: An example of a Vehicle-in-the-Loop (VitL) setup, illustrating a real car on a test track connected to a high-fidelity simulator like CARLA that generates virtual traffic and sensor data. Adapted from Drechsler et al. (2022) and Cao et al. (2023).

These examples show a clear trend towards using powerful, game-engine-based simulators to test autonomous vehicles. This approach increases safety and efficiency, and it bridges the gap between pure simulation, which lacks real vehicle dynamics, and physical testing, which is often not repeatable [Cao+23]. Furthermore, some frameworks extend this concept to directly stimulate the vehicle's sensors. For instance, a Radar Target Simulator (RTS) can feed artificial radar echoes from a virtual scene to the vehicle's real radar sensor, allowing for end-to-end validation of the entire perception and control pipeline [Die+21].

The versatility of the X-in-the-Loop concept is shown by its application in other domains. In marine robotics, a VIL framework was developed to test the long-term autonomy of a robot swarm. In this system, a real Autonomous Surface Vehicle (ASV) interacts with many simulated underwater sensor nodes to validate complex cooperative behaviors without the high logistical cost of deploying a full physical swarm [Bab+20]. In the aerospace domain, the RFlySim platform uses an FPGA-based HIL system to create a high-fidelity simulation for safely testing UAV autopilot systems in a lab, which reduces the need for expensive and risky outdoor flights [Dai+21].

The evolution of these methods points towards an even more integrated future. This includes the introduction of "Scenario-in-the-Loop" (SciL) frameworks that aim to completely blur the lines between real and virtual testing [Sza+21]. These next-generation systems rely on creating comprehensive digital twins of the entire test environment and coordinating a mix of real and virtual objects to run complex, mixed-reality test scenarios [Sza+21].

2.2 Digital Twins

A key concept that underpins many modern "X-in-the-Loop" frameworks is the Digital Twin (DT). The DT serves as the virtual counterpart to a physical system, acting as a virtual copy that enables real-time monitoring and simulation [AA23]. The core idea is to create a digital information model of a physical system that stays linked to it throughout its entire lifecycle [Gri17].

This model, first called the "Information Mirroring Model," has three primary components: the physical product, its corresponding virtual model, and the data connection that links them [Gri17; AA23]. A conceptual diagram of this structure is shown in Figure **??**. The virtual model is more than a simple geometric shape; it is often a complex simulation that can model a system's mechanical, electrical, and software properties [Len+21]. The data connection is bi-directional, allowing sensor data to

flow from the real world to update the virtual model. In turn, the virtual model can send commands back to control or optimize the physical system [Gri17; Len+21]. This continuous, synchronized data exchange is the defining feature of a Digital Twin [AA23].

Figure 2.3: The foundational concept of a Digital Twin, illustrating the three core components: the physical entity, the virtual model, and the bi-directional data connection that links them. Adapted from Grieves et al. (2017).

In robotics, Digital Twins are often built using specialized simulation software. The Robot Operating System (ROS) typically acts as the middleware connecting the virtual simulation to the physical hardware. For instance, Stączek et al. used the Gazebo simulator with ROS to create a DT of a factory floor, which they used to test and optimize the navigation algorithms of a mobile robot in narrow corridors [Stą+21]. A similar approach was taken by R. Singh et al., who developed a DT of a greenhouse in Gazebo to validate a deep learning-based harvesting robot [Sin+24b]. Other simulators like CoppeliaSim and Webots are also common. Magrin et al. used CoppeliaSim and ROS to create a DT as a learning tool for mobile robot design [Mag+21], while Marques et al. used Webots for an Automated Guided Vehicle (AGV), synchronizing it via an OPC-UA server [Mar+24]. These examples show a common method of using traditional simulators to model robot kinematics and sensor feedback for closed-loop testing.

More recently, modern game engines have become a popular choice for creating Digital Twins, as they offer higher-fidelity graphics and more realistic physics. The Unity game engine, in particular, is used to build powerful, performant, and visually rich virtual environments. This can be seen in Figure **??**. For example, Pérez et al. used Unity3D to develop a DT of a multi-robot cell that included an immersive Virtual Reality (VR) interface for virtual commissioning and operator training [Pér+20].

Figure 2.4: A comparison of robotic Digital Twin environments, showing a typical view from a traditional simulator (left) versus a high-fidelity visualization from a modern game engine like Unity (right).

The technical capabilities of these engines are also a key factor. Yang et al. used Unity and its integrated NVIDIA PhysX engine to simulate the complex physics of a UAV. They also demonstrated how to create virtual sensors, such as a LiDAR, directly within the game engine using its raycasting API [Yan+20]. The performance and reliability of these game engine-based frameworks have also been a focus of research. Kwon et al. developed a safety-critical DT in Unity and ROS 2, achieving a low data-transmission

latency of just 13 ms for predicting collisions [Kwo+25]. Similarly, M. Singh et al. created a Unity and ROS-based DT and conducted extensive performance validation, reporting a communication latency of 77.67 ms and a positional accuracy of 99.99% [Sin+24a].

2.3 Mixed Reality

Beyond the testing paradigm and the digital twin, the way a user interacts with the system is another critical part of a modern robotics framework. Virtual, Augmented, and Mixed Reality (VAM) have become promising technologies for improving the information exchange between humans and robots [Wal+23]. In robotics, Augmented Reality (AR) is an especially powerful tool for enhancing Human-Robot Interaction (HRI) by integrating 3D virtual objects into a real-world environment in real-time [MV20].

The relationship between these technologies is formally described by the foundational "Reality-Virtuality (RV) Continuum" concept, first introduced by Milgram and Kishino [MK94; Ska+21; MV20]. As illustrated in Figure **??**, this continuum is a scale that is anchored by a purely real environment at one end and a completely virtual one at the other [MK94; Ska+21; MV20].

Figure 2.5: The Reality-Virtuality Continuum, illustrating the spectrum from a real environment to a completely virtual one. Mixed Reality (MR) encompasses both Augmented Reality (AR) and Augmented Virtuality (AV). Adapted from Milgram & Kishino (1994) [MK94] and Walker et al. (2023) [Wal+23].

A conventional Virtual Reality (VR) environment represents the continuum's virtual endpoint. In VR, the user is totally immersed in and can interact with a completely synthetic world [MK94]. This approach is very useful for HRI research, as it allows for testing interactions with virtual robots in scenarios that might be unsafe or too expensive for physical hardware [Wal+23]. The general term Mixed Reality (MR) describes the entire spectrum between the two extremes, where real and virtual worlds are merged within a single display [MK94]. MR is made up of two main categories: Augmented Reality (AR) and Augmented Virtuality (AV) [MK94; MV20]. AR involves augmenting a real environment with virtual objects [MK94]. This allows HRI researchers to place a robot's 3D data and intentions directly into the user's physical space [Wal+23]. The opposite is Augmented Virtuality (AV), where a primarily virtual world is enhanced with elements from the real world, like live video feeds [MK94].

2.4 The VERA Framework and EMARO

2.5 Comparison of Simulation Engines?

3 Requirements

4 Concept and Implementation

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4.1.1 Integration of Unity, ROS 2, and EMAROS

components, their responsibilities, and deployment setup.

4.1.2 Communication Concept

Topics, message types, timing, synchronization ...

4.2 Development Milestones

4.2.1 Base Integration

Initial data flow, messaging bridge, and minimal scenes.

4.2.2 Realization of the Digital Twin

Robot modeling, environment setup, and synchronization.

4.2.3 Interaction Scenarios

Scenarios and scripting.

4.2.4 VR Integration

Devices and implementation, mabybe before Interaction Scenarios?

4.2.5 Pure Virtual Model

Implementation and use cases without the physical counterpart.

5 Evaluation

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5.1.1 Test Scenarios

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5.1.2 Metrics

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5.3 Discussion

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summary of the work and discussion of future research directions.

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I hereby declare that I have written this thesis independently and without unauthorized assistance. I have not used any sources or aids other than those indicated. All passages taken verbatim or in spirit from the works of other authors have been properly acknowledged and cited.

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