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DEVELOPMENT OF A COMPLEX SOLUTION FOR A HUMAN-ROBOT INTERACTION AND OPERATORS TRAINING USING VR-INTEGRATED DT FRAMEWORK

The object of research is the process of managing human-robot interaction through the virtual reality-integrated digital twin system. The problem addressed in the research is that, despite active development of architectural solutions, there are barriers to fundamental research and operator training due to the prohibitive costs, technical complexity, and proprietary restrictions of industrial-grade robotic hardware.

The obtained results are the creation of a comprehensive, scalable, and flexible digital twin architecture, implemented through a functional prototype. The prototype digital twin framework is an extensible tool for testing research strategies and can be adapted for specific tasks or equipment. The implementation synchronizes a low cost 6-degrees-of-freedom manipulator with its digital model using the Unreal Engine. Analysis of the application areas of the developed system highlights the potential of virtual reality to improve human-robot interaction.

These results were made possible by a complex approach combining architectural design and experimental prototyping. Unlike industrial solutions, which focus on specific technologies, a general approach to system design was applied. A significant advantage of focusing on general principles is that they can be developed without recourse to using complex real systems, which are associated with safety, accessibility, and cost issues.

The proposed solution is designed to enable systematic testing of a wide range of user interface designs, situational awareness tools, interaction, and collaboration strategies in a risk-free virtual environment. The underlying design and software will be publicly available, enabling researchers to use a standardized yet flexible approach to develop human-robot interaction systems based on the results presented in this research.

Keywords: *digital twin, user interaction, immersive learning, virtual reality, augmented reality.*

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1. Introduction

Digital twins (DT) are virtual models that replicate physical objects, systems, or processes in real-time. This means that the DT continually exchanges data with the physical original [1]. By linking real-world data with virtual environments through sensors and other digital infrastructure, DTs enable the generation of new insights, for example, in system evaluation, user interface design, and training, without the access limitations, costs, and safety issues that characterize the use of physical systems. Technology has widespread applications across various industries, including manufacturing [2], healthcare [3], urban planning [4], and the energy sector [5].

DT design is still developing, and researchers are examining how DT platforms can be effectively employed for prototyping, lifecycle analysis, and virtual testing [1]. Advancing this capability will require a systematic investigation into how to optimize visualization, collaboration, and learning processes within such environments. Digital visualization technologies enable designers to create arbitrary, multisensory representations of underlying data or system state. The DT can be arbitrarily augmented to enhance user experience by presenting information or cooperation tools tailored to specific user groups or tasks. These additions, however, must be evaluated with a real system.

A key issue in the use of DTs is simulation fidelity [6]. Where DTs are used for training and process optimization, efficiency, and especially the transfer of outcomes from the digital model to real systems, are crucial [7]. Multisensory feedback also affects task performance in VR and information perception [8]. It can be argued that the same principles apply to any DT, and therefore, this fundamental research is not limited to specific applications. Therefore, research devoted to DT design in the human-robot interaction (HRI) domain is relevant.

With ongoing technological development, human operators are facing complex tasks, including industrial digitalization and the use of integrated control systems. Therefore, there is a need for solutions that improve operators' skills across various dynamic environments, increasing their adaptability and flexibility [9].

Virtual reality (VR) and augmented reality (AR) technologies provide an effective way to visualize and deliver complex information. They provide a spatial representation of data, creating an immersive effect that can improve perception, interpretation, and understanding. Users tend to perceive VR/AR-based interactions as similar to real-life experiences. This perceived realism positively affects operator productivity, as people immerse themselves more deeply in the work process and can interact with their DT via an intuitive multimodal interface [10].

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The development of serious games and virtual simulations based on augmented reality technologies is a promising area of virtual learning with great potential for integration across various industries [11]. Serious games are simulators with gamification elements that immerse users in learning and training environments [12]. Integration of VR and gamification mechanisms provides a high-quality learning and training experience. The integration of gamification elements increases student motivation and enhances the overall learning experience. This approach facilitates learning by making it easier to acquire knowledge and by creating a more conducive environment [13].

Serious games and virtual simulators are based on a static model with predefined rules and are not connected to real equipment in real time. However, for example, in user interface or learning strategy testing, it can be helpful to have access to real equipment and observe changes in real time. In such situations, DT-based learning platforms become particularly useful.

According to the CIRP Encyclopaedia of Production Engineering, a DT is a digital representation of a product or system that comprises its selected characteristics, properties, conditions, and behaviors, using models, information, and data within a single or multiple life cycle phases [14].

DT technology allows for the creation of a virtual representation of a physical system. The safety of human-robot interactions can be improved through real-time monitoring of equipment, human actions, and the surrounding environment. DT is an integration layer that connects key technologies, thereby improving communication and coordination between human operators and automated systems [15].

DTs are most effective when the physical system changes over time and when sensor data reflecting these changes can be continuously captured. The DT concept is valuable in the manufacturing domain because it supports the development, validation, and updating of individual models within a unified framework [16].

Some challenges associated with DT may not be unique and may be shared with other, better-studied areas, such as building information modelling, advanced control systems, computer-integrated manufacturing, and other domains [17]. However, DT brings all these solutions and problems together, creating a very powerful tool that can be used across various areas.

DT models have been successfully implemented across a wide range of application domains, including manufacturing, energy, aerospace, engineering construction, cities, healthcare, agriculture, and so on. In manufacturing, DTs are used for full-scale factories, precision parts, macro manufacturing systems, and product production processes. DT models can be categorized into several sub-applications in the robotics domain: industrial robots, mobile robots, line-following robots, and robot arms [18].

DT models are designed for industrial applications and scientific research, focusing on bridging the gap between virtual and physical entities. For instance, research with FANUC robots using virtual reality demonstrates how an immersive interface can improve the accuracy of task planning and system evaluation [19]. Another important issue is the development and implementation of a bidirectional real-time data synchronization system [20]. In addition, research into multimodal human-robot interaction can be scaled using cloud-based VR platforms, such as SIGVerse [21]. Such developments and research involve creating DTs for industrial equipment, a costly process that requires implementing complex industrial communication protocols. There are studies that describe the process of developing DTs for simpler equipment to integrate into the educational process [22]. In the paper "Simulation and Real Time of VR Controlled Robotic Manipulator Using ROS", researchers propose using Unity 3D to provide a virtual environment for ROS to ensure communication with the physical robot [23]. Understanding the complex architecture of frameworks such as the Robot Operating System (ROS) library remains necessary for working with the proposed systems.

Literature review reveals the following unresolved issues:

– there is a wide variety of industrial equipment, but often the offered architectural solutions are designed for specific equipment or based on specific technologies. Therefore, there is a need for fundamental and configurable architecture concepts that can be scaled up;

– industrial equipment is expensive and difficult to configure, which makes testing research theories more resource–intensive. Therefore, it is necessary to develop a framework that will allow testing user interfaces or interaction strategies before scaling them up;

– another unresolved part of the problem is the undefined application areas for DTs in combination with virtual reality to unlock their full potential.

This problem persists due to the lack of standardization and the wide variety of tasks that need to be addressed. Currently, the field of DTs and HRI is in the stage of generating ideas and accumulating knowledge, so research in this area is relevant. *The object of research* is the process of managing human-robot interaction through the virtual reality-integrated digital twin system.

The aim of this research is to develop a complex fundamental solution for a VR-integrated DT framework in the HRI domain.

To achieve this aim, the following objectives were accomplished:

– to develop a simple, scalable, and flexible DT architecture;

– to create a prototype DT that can be implemented using affordable tools and a robot;

– to investigate how DT systems can be systematically extended beyond visual replication to incorporate multisensory augmentation, advanced visualization, gamified learning strategies, enhanced situational awareness, and cooperative interaction.

This will enable the creation of a cost-effective, safe, and reproducible method for developing and testing HRI strategies before implementing them on expensive industrial equipment.

2. Materials and Methods

The methodology of this research combines theoretical and experimental research methods. To conduct a structured literature review, a comparative analysis was used, which allowed the study of existing architectures for HRI based on DT and the identification of unresolved issues. System analysis was used to identify relationships among the physical, digital, and interface levels and to identify hardware-independent architectural principles. The theoretical research methods mentioned above were used because this research is conceptual and identifies general and scalable HRI principles. The experimental research methods used include architectural design, experimental prototyping, and systematic evaluation of user interaction strategies.

The object of research is the process of managing HRI through the virtual reality-integrated DT system. The main hypothesis of this research is that a prototype DT system can allow for the development and verification of user interaction strategies before scaling them up to industrial hardware. The assumptions adopted in the work are that the robot-environment coupling is modelled as a compliant dynamic interaction rather than a rigid position-tracking task.

The system's physical asset is a 6-DOF robotic manipulator driven by servo modules. The robot is controlled by an M5Stack ESP32 (M5Stack Technology Co., Ltd, China) microcontroller. Additionally, peripheral devices such as joysticks were used for manual input. Meta Quest Pro (Meta Platforms, Inc., USA) headset and controllers are used to provide a VR user interface. The DT model and simulated environment were developed using Unreal Engine (Epic Games, Inc., USA). The software for the M5Stack microcontroller was written using the Arduino IDE (Arduino SA, Italy).

3. Results and Discussion

3.1. Digital twin architecture design development

System architecture is a key component in collaboration technologies. System architecture determines how easily it is to add new functionality, modify existing components, or connect additional equipment. This section describes various aspects of the system, including the reference architecture scheme, data flow diagrams (DFDs), and IDEF0 (integration definition for function modelling) methodology, which is a component of the structured analysis and design technique (SADT).

Fig. 1 presents the architecture for a system that provides HRI through a DT. The system is divided into three connected layers: the real world, the digital world, and the interface level. This topology enables real-time bidirectional synchronization between the physical and DTs. DT provides a safe way to control robotic systems by delivering multimodal feedback to the user.

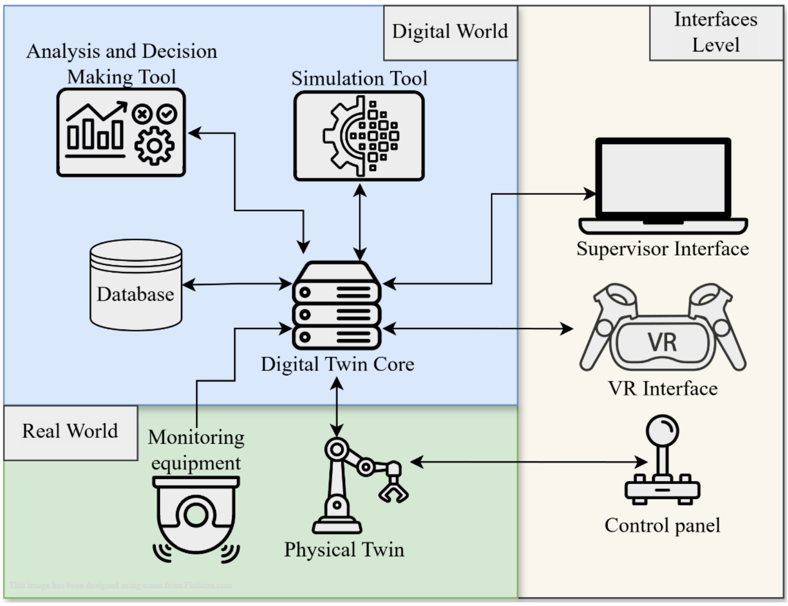

Fig. 1. Architecture scheme

The real-world layer represents an operating environment where the actual tasks are performed. The physical twin is real equipment that performs physical tasks in a physical environment. Ideally, it should be equipped with internal sensors to transmit status data to the DT. If built-in sensors are not installed, the status can be captured using additional monitoring equipment. Such monitoring equipment includes external sensor devices that capture the unstructured environment and the robot's interaction with it. This data provides the contextual awareness necessary to simulate the environment with high accuracy and to provide real-time updates on its status, not just the equipment. External sensors also help detect faults that may be impossible for built-in sensors to detect, such as software malfunctions.

The digital world layer is a set of tools for processing, storing, and reproducing data, which also manages state synchronization and executes high-level logic for HRI. DT Core is a centralized server that acts as a data broker. It processes real-time data streams from the physical level and distributes them to peripheral digital instruments. It provides two-way synchronization, allowing the virtual model to reflect the physical state in real time. The simulation tool models the robot's behavior in a virtual environment. It enables predictive analysis, collision detection, and scenario testing without risking physical hardware. The analysis and decision-making tool processes incoming data, identifies anomalies, and generates control decisions. The database module is responsible for logging historical telemetry, error logs, and operational datasets for post-process analysis or machine learning training. It is important to note that the scheme shows DT components that can be deployed on a single device.

The interfaces level represents several interfaces for human interaction with the system, catering to different levels of immersion and control authority. A virtual reality headset and controllers provide an immersive teleoperation environment. The VR interface is directly connected to the digital twin core, allowing the operator to manipulate the virtual robot and get multi-modal feedback. Supervisor interface, represented by a standard workstation, provides a 2D dashboard for system configuration, telemetry visualization, and supervisory control, receiving data from the core. The physical control panel has a direct connection to its physical twin. This involves the use of traditional or safety-critical manual control that goes beyond the digital abstraction layer to provide direct actuation.

Bidirectional data flows are the basis of the architecture and connect all system components. Fig. 2 visualizes the data flow diagram (DFD) for the presented architecture and outlines the functional decomposition and information flow paths within the DT architecture.

The presented system can be divided into two parts (separated by a dotted line). On the right is the physical layer, which represents physical equipment and can function without the left part. On the left is the digital layer, which implements high-level control logic over physical equipment using a set of tools.

Execute physical action process models the robot's interaction with the unstructured world. This node captures the kinematic transformation in which motions result in a change in the state of the physical environment. The environment reacts to the interaction through contact forces, and the actual kinematic state is returned to the hardware, providing the physical feedback loop. Process 4.0 models the interaction between a robot and the environment as a flexible, dynamic interaction rather than rigid position tracking.

Process 8.0 provides direct control. The manual operator relies on direct visual feedback from the physical environment and telemetry on a control panel to enter commands. This process sends direct commands to the robot, ensuring immediate intervention capabilities during emergency scenarios. If the physical equipment is not connected to the DT, this remains the only way to control this equipment.

Process 2.0 (operate digital twin) is the central data broker of the digital layer, where all data flows from other processes converge. Computationally intensive tasks are distributed to peripheral modules. Process 7.0 predicts future states based on the current system state and returns a simulated state behavior validation. Process 6.0 is responsible for data processing and decision-making. The database stores data created by the system for post-hoc analysis.

The interface between digital logic and physical reality is managed through a layered control approach. Process 3.0 (control physical twin) is the communication layer. It converts abstract tasks from the core into low-level commands for the physical twin and filters raw telemetry into standardized telemetry for further processing. Additionally, the state of the physical environment is continuously observed by Process 5.0 (monitor environment), which discretizes the environment state for the DT.

The architecture supports asymmetric collaboration through distinct functional pathways. Process 1.0 controls the data flow for two operators. The VR operator engages in immersive control via VR input and receives multisensory data back from the system. At the same time, the operator-supervisor interacts with the system through a separate interface, at a different level of interaction, and not immersed in the virtual environment.

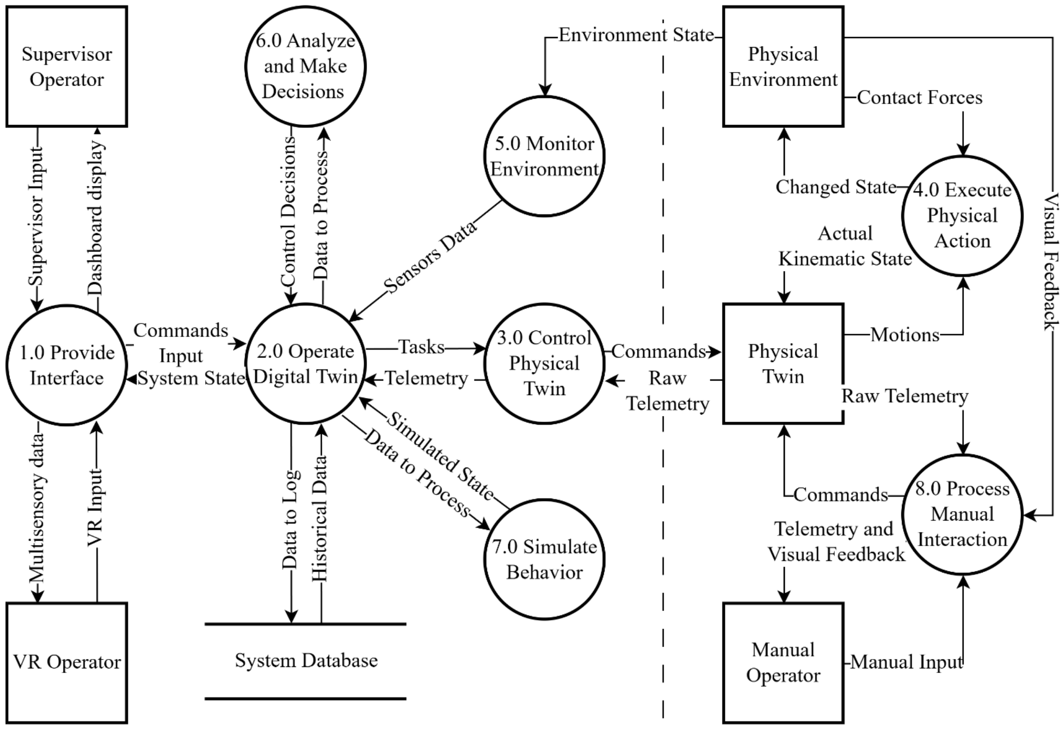

Fig. 2. Data flow diagram (DFD)

Using the structured analysis and design technique (SADT), the IDEF0 diagram was created to present the decomposition of functions, categorized by Inputs, controls, outputs, and mechanisms. The context diagram is presented in Fig. 3.

Manage human-robot interaction – the primary process that describes the information system. System inputs are environmental state and operator input, which are the primary sources of data for the system's operation. The operation of the system is regulated by a set of control elements, including interface protocols, task requirements, kinematic limits, environmental constraints, authorization levels, optimization rules, and simulation constraints. Mechanisms that enable the implementation of functions are a mix of hardware components (physical twin, external sensors, user's input hardware) and software entities (simulation tool, system database, analysis and decision-making tool). The process generates telemetry data for system monitoring and multimodal output (e. g., haptic, visual, or auditory feedback) for the operator.

The main process is decomposed into three sub-functions. Fig. 4 shows the decomposition of the contextual representation to obtain a more detailed understanding of the processes occurring within the system.

Processing input data aggregates raw signals from the environmental state and the operator's input using external sensors and the user's input hardware to capture data. The function filters inputs based on Interface Protocols and validates user commands against authorization levels. The processed signals are converted into structured sensor data and normalized command input, which serve as the input data for the next block.

The operating digital twin node represents the system's main logic block. Unlike traditional direct-control architectures, this system processes inputs through a virtual abstraction known as the DT. Using the simulation tool, system database, and analysis and decision-making tool, the system predicts outcomes and optimizes trajectories before physical execution. The simulated state output of the digital model and the control decisions are returned as inputs, providing a mechanism for continuous state estimation and error correction.

The A2 block's output is commands, which serve as the control robot block's input data. The control robot block is the level of execution of physical actions. This block is a controller for physical equipment (robot) that is regulated by kinematic limits and environmental constraints. The output of the last block and the system as a whole consists of telemetry data and multimodal output, completing the interaction cycle.

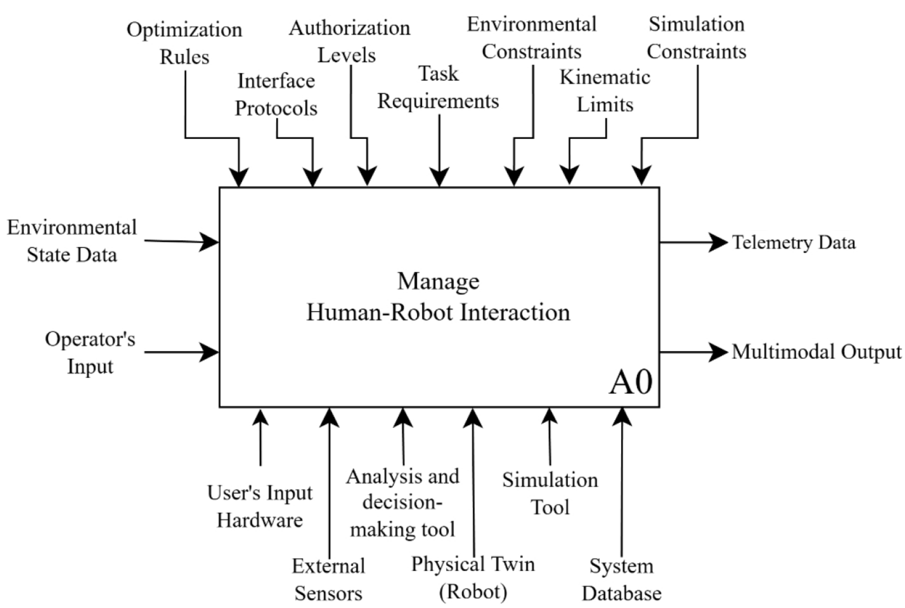

Fig. 3. Context diagram in IDEF0 notation

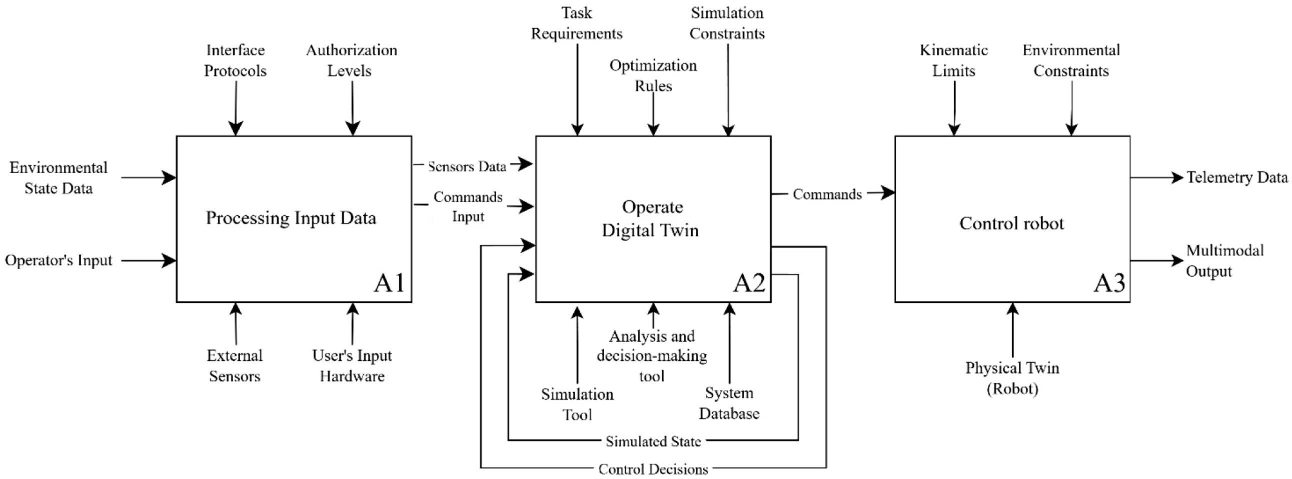

Fig. 4. Decomposition diagram

3.2. Implementation of a cheap digital twin prototype

This section describes the implementation of the prototype DT framework, using the example of a 6DoF robot with Amazon. The system architecture has been simplified for maximum simplicity and accessibility. The proposed framework contains basic functionality that can be extended using the principles and architecture scheme described in the previous section. The DT provides an additional interface for users to interact with the equipment. Unreal Engine is used as a tool for presenting DT. Communicating between the physical device and the DT application implemented via the COM port. To immerse the user in the digital environment, a Meta Quest Pro VR headset connected to a computer via Quest Link was used.

The DT provides a user interface for entering commands. In this simplified system, the equipment's behavior was not simulated; instead, the digital shadow principle was used. The control command is sent to the physical device for execution, and the DT state is updated based on the position received from the physical twin. The physical system must remain operational even when disconnected from the DT. If the robot is controlled directly by its input devices, the DT performs the function of a digital shadow. This means that it receives data from its physical twin and repeats the actions.

The physical system is a simple 6-DOF commercial robot manipulator that can be controlled using a simple, IoT-enabled microcontroller. Each joint is equipped with a servo module for rotation. The M5Stack series of ESP32 microcontrollers was used because they can easily be configured for a range of input and output devices, programmed in the Arduino environment using MicroPython or the UIFlow graphical interface, and come with a wide range of sensors to generate test data. M5Stack is equipped with three buttons and a display, which serve as a basic user input and output layer. Additionally, the Joystick was connected using the I2C interface as the main device to control the servo's angle.

The physical control software interacts with the PC running the DT to ensure data exchange and interaction. The digital representation uses a digital 3D replica of the physical system using the Unreal Engine to visualize and control behavior. Digital models, just like the physical robot, can be assembled in various configurations. A Meta Quest Pro provides the VR and AR user interface. DT's operation is enabled by the creation of a two-way data flow, but the model can also function as an isolated virtual simulation. The virtual environment enables the possibility to add multisensory cues to represent information about (changes in) the state of the physical device. Extended reality provides opportunities to integrate a DT into a changing environment. The underlying code is available at GitHub [24]. Fig. 5 shows examples of how the developed system can be used.

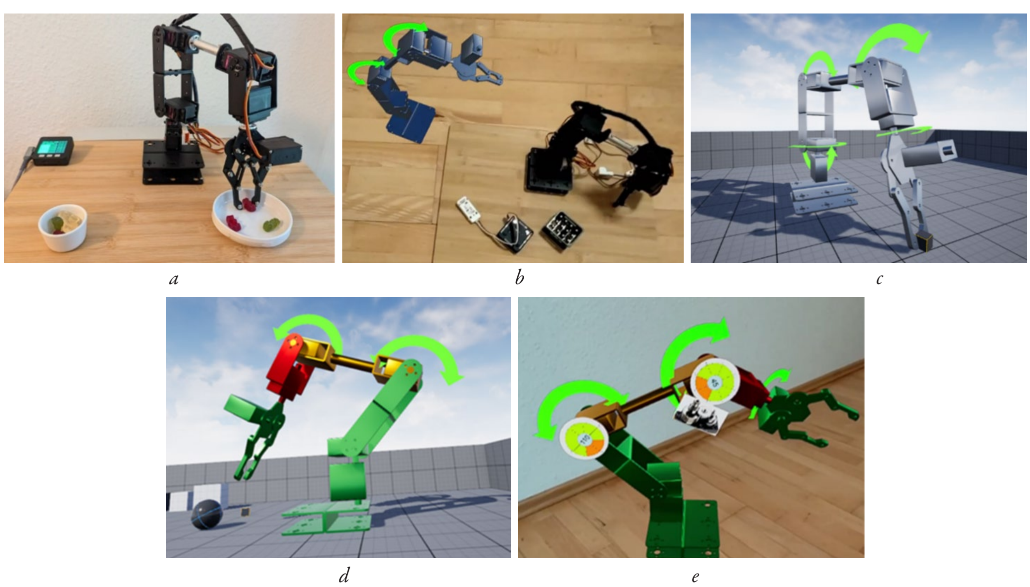

Fig. 5. Examples of use of the developed system: *a* – physical twin; *b* – augmented reality model next to physical; *c* – virtual reality model with movement direction cues; *d* – system state visualization; *e* – model with pictorial signals

3.3. Application areas and interaction strategies investigation

DTs are commonly seen as faithful replicas of their physical siblings. There is compelling evidence that the addition of multisensory cues, even if they do not occur in real environments to virtual environments, enhances not just user experience but also speeds training progress and, crucially, aids the transfer of learning from digital to real systems [7, 8]. The design of multisensory interfaces that enhance interaction, cooperation, and learning in DTs, therefore, presents a range of opportunities for research and development in the following areas:

Visualization: a range of visualization techniques can be used to provide users with information: color can, for example, highlight the system state; additional visual cues can indicate potential affordances in the system; and text or graphical objects linked to specific system components can inform users. These visual signals, which go well beyond what can be presented in physical systems, can be easily implemented in the Unreal simulation and then systematically evaluated. The output of instrumentation, for example, temperature sensors on the physical servos, can be visualized on the DT.

Multisensory augmentation: the DTs are typically thought of as visual representations – but there is no need to limit signal representations to one modality. Auditory, haptic, and even vestibular cues, taste, and smell can be used to signal information, for example, to draw attention to key locations or events, or to help recreate an immersive ambient environment.

Learning: augmented DTs provide substantial opportunities for learning by presenting learners with relevant information, guiding attention or actions, monitoring engagement and progress, and providing feedback. It is well known that gamification of tasks, by providing progress statistics, challenges, and quizzes, enhances cognitive, motivational, and behavioral learning outcomes [25]. Simplified systems that offer sufficient complexity, such as the proposed robot, provide a rich environment to develop, systematically test, and optimize learning systems.

Situational awareness: DTs are particularly useful where systems are remotely operated. In these instances, operators have limited views of the system and typically limited situational awareness. The VR/AR system enables researchers to experiment with technologies and signal representations that enhance situational awareness in a safe and replicable environment.

Cooperation: gaming environments, such as the Unreal Engine environment used to implement the DT, provide rich multiplayer environments that enable multiple users in remote locations to interact within the same environment.

The environment provides opportunities to develop general principles for collaborative virtual systems: a) signal representation, developing strategies for the presentation of task and user-specific information; b) information sharing, developing systems to share relevant information among collaborators effectively, and c) remote interaction between human users, but also with potentially multiple real instantiations of the model systems. Multiple robots, for example, could be controlled, monitored, or optimized for cooperative tasks.

3.4. Discussion of results

The architecture for HRI proposed in this research is described using various diagrams to demonstrate different aspects of the system. To describe architecture, a diagram (Fig. 1) was created to depict the components of the system and then supplemented using a data flow diagram (Fig. 2) and a structured analysis and design technique (Fig. 3 and Fig. 4). This part of the results covers the lack of fundamental and configurable architecture concepts that can be scaled up upon requirements. Unlike [19–21], which uses specific equipment for system development, the proposed architecture serves as a reference point, enabling reconfiguration using common approaches. This was made possible by generalizing the approaches used in developing HRI systems.

The developed prototype DT framework addresses the need for a tool to test user interfaces or interaction strategies before scaling them up. The system bridges the gap between simulators and real-world equipment by integrating VR and gamification elements in the form of cues. Unlike [22, 23], where the physical equipment was designed by the authors, the proposed system uses existing equipment and creates a digital model for it, which requires fewer resources.

The "Application areas" results sub-section describes how a developed system can fully leverage the advantages of Virtual Reality to enhance user immersion in the system. This part of the obtained results covers the last problematic part defined in the problem statement section.

The primary limitation is the mechanical fidelity of the prototype. The low-cost servo motors used in the 6-DOF robot lack the precision and torque of industrial servomotors. Although the interaction logic is correct, the kinematic data may contain noise that would not be present in a high-tech robot. Future studies should take this into account when using this framework, or improve the equipment's accuracy by using better equipment at a higher price.

The shortcomings of the research lie in the fact that no experiment was conducted to verify the transfer of learning from the DT to physical equipment. The development of this research should focus on developing and conducting an experiment to investigate the transfer of learning from the DT to physical equipment. This direction is relevant because it can help integrate training on DTs into the training process for industrial equipment operators, reducing costs and increasing safety.

4. Conclusions

1. A simple, scalable, and flexible DT architecture that does not depend on specific equipment and offers general principles for creating systems in the robot-human interaction domain was developed. Industrial solutions are focused on specific equipment, while scientific developments are often based on self-developed hardware. The developed modular reference architecture offers the feasibility and ability to be adjusted accordingly to the tasks. The main distinguishing feature of the proposed architecture is that it is not dependent on specific equipment but offers general principles for building HRI systems.

2. The implemented prototype DT framework is a minimalist digital-physical system, a widely available and low-cost 6doF robot arm. A robot can be directly controlled by a microcontroller or via the computer that also runs a simulation of the DT, providing a VR or AR interface to the user. The framework connects the physical robot and its DT, ensuring synchronization and real-time data exchange. The simultaneous use of real and DT systems enables the development of generic knowledge in a cost-efficient, safe, replicable, and shareable manner, while ensuring the transfer of outcomes between virtual and physical systems remains intact. While industrial solutions involve high costs for industrial equipment and licenses, the developed prototype uses inexpensive equipment and affordable tools.

3. DT systems can be systematically extended beyond visual replication and outlines the application areas of novel digital interaction strategies to ensure that they translate into transferable outcomes. The use of virtual or augmented reality provides the user with task-relevant information in an immersive environment, which improves user comprehension and reduces task errors. Gamification elements can increase learner motivation and engagement, leading to faster acquisition of control strategies. Industrial solutions are difficult to customize for learning tasks, and research in HRI and digital twins often focuses on positioning accuracy, whereas the developed approach proposes the use of multimodal augmented reality and game-based learning strategies.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has associated data in a data repository.

Use of artificial intelligence

The authors declare the use of AI:
– During the preparation of this work, Grammarly was used.
– The specified AI was used in all sections except the bibliography.
– Grammarly was used for grammar, spelling, and punctuation checking.
– During the use of this tool, the authors reviewed the recommendations provided by the tool, and the decision to apply the recommendations was made by the authors.
– The use of AI improved grammar, spelling, and punctuation, but had no effect on the results obtained.

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Authors' contributions

Yevhen Palazhchenko: Conceptualization, Methodology, Software, Writing – original draft, Visualization; ***Vira Shendryk***: Conceptualization, Validation, Formal analysis, Writing – review and editing, Supervision; ***Georg Meyer***: Conceptualization, Formal analysis, Writing – review and editing, Supervision.

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