Challenges of Simulated Humanoid Robots for Construction Tasks in the Immersive Environment*

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Abstract— **Humanoid robots offer significant potential in various industries, including construction, where they can address inefficiencies and safety concerns. However, integrating them faces challenges like economic feasibility and technical limitations. Simulation plays a vital role in assessing humanoid performance. This paper compares human and humanoid welders in a simulation of welding shear studs on a composite floor. Results highlight differences in production rates and task completion times, emphasizing the need for machine learning to enable humanoid efficiency. Simulation aids in understanding and overcoming challenges in humanoid integration, facilitating progress in robotics technology.**

I. Introduction

Robotics has revolutionized various industries by automating repetitive tasks, enhancing precision, and improving efficiency. Humanoid robots are complex machines designed to resemble and mimic human movements, capabilities, and behaviors. These robots are typically characterized by a human-like appearance, including features such as a head, torso, limbs, and sometimes even a face [1]. The inception of humanoid robots has been traced to the early 20th century, when Japan emerged as a pioneer, addressing labor shortages with innovations like WABOT and ASIMO while spearheading construction automation [2].

In part, due to DARPA's Robotics Challenge, more researchers and developers have been creating humanoids that can conduct human tasks [3]. Initially, human tasks were simple, but these have become more complex with time, allowing robots to imitate and perform human jobs [3, 4]. Recent developments include Softbank's Pepper[5] and Toyota's T-HR3[6], showcasing advancements in human-robot interaction and virtual mobility services. In healthcare, humanoids have started to be used for tasks such as assisting patients with mobility and providing companionship to the elderly [7]. Humanoids can also be utilized in medical training simulations, enabling minimally invasive surgery [8]. In education, humanoids have been tested as tutors [9]. Finally, humanoid robots like NASA's Robonaut are being developed for space exploration missions [2].

Across these sectors, robotics drives innovation, safety, and productivity [9]. In the construction industry, robots have been increasingly incorporated to perform repetitive tasks and to help humans with tasks that are physically taxing [10, 11]. These are especially attractive in the construction industry, where issues of inefficiency and injuries are prevalent [12]. However, most robots are pre-programmed to perform single tasks, such as brick-laying robots [10, 11]. Robots have become more advanced with the implementation of imitation learning, where robots are trained by human demonstrators [10]. Fully autonomous robots are rare and mostly designed for single-tasks, such as robots that use SLAM technology to navigate environments and collect data, or robots like Tybot that perform rebar assembly [10]. Humanoid robots for construction are still mostly in development, but important advances have been made. For instance, Boston Dynamics Atlas Robot has an impressive agility [13]. AIST has advanced in developing a humanoid for the construction industry, which has been shown to place plaster boards successfully [3]. Researchers are also advancing the study of virtual reality to enhance human-robot collaboration [14].

Robotics and automation in construction face several barriers, including economic feasibility, worries about safety, and lack of required skills [15, 16]. Robots face several limitations, including navigating complex environments and adapting to changes [15]. This is in addition to human robots' limited dexterity [3], maintenance needs, and regulatory hurdles. Overcoming these limitations will require technological advancements, collaboration between stakeholders, and the development of robust regulatory frameworks to ensure safety and efficiency in construction robotics applications. And, importantly, it highlights the need for realistic simulations incorporating the robot's challenges in the construction environment.

This research contributes to the understanding of humanoid use in the construction industry. It uses simulation and an immersive environment to evaluate the potential advantages of using a humanoid in a specific construction task. The immersive environment allows us to develop scenarios where humanoids face real-life constraints. The humanoid model seeks to understand the robotics system's capability to cope with unstructured environments (construction) and understand behaviors on automating construction tasks (performed by humanoids as artificial agents). The aim is to understand morphologically how to better adapt humanoids to different environmental (physical) conditions in unstructured environments.

II. SIMULATION

Simulation is the action of imitating a situation or a process. It allows experimenting in a safer, inexpensive way without disruptions. The advantages of simulation include building models with varying complexity, incorporating random variables, explicitly considering time, and providing graphical animation for better understanding [17].

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A. Simulation in Construction

Simulation in the construction management industry was initially limited due to the complexity of simulation itself and the use of resources that entail applying it, such as time and money [18]. Yet, in the last decades, several software have been developed for simulation in the construction industry; one of the pioneer software for cyclical tasks in construction is CYCLONE [19]. With the advance of technology and the rapid increase of humanoids, simulation can be used to test the potential use of robots in cyclical construction tasks.

Developing and training complex robots for real-world applications is very costly, so simulating construction tasks using robots offers several advantages before testing them in the physical environment, such as identifying and addressing potential issues before deployment on actual construction sites and gathering data to inform the development of more advanced and effective robotic solutions. The industry is already making progress in that direction. Most of the humanoids that are nowadays in use in construction have been previously simulated by Nvidia's Omniverse platform, Isaac Sim. This platform allows researchers to test their robot designs virtually before being physically developed.

B. Virtual Reality in Construction

In addition to the advantages of simulating construction tasks using robots, virtual reality (VR) simulations can further enhance the efficiency of construction project management and coordination. VR simulations aim to create a sense of "presence" and "immersion" for users, essential for facilitating cognitive, motor, and functional rehabilitation [20]. Drawing from the transformative applications of virtual reality (VR) in neurorehabilitation, it can be inferred that VR holds promise for utilization in construction sites [21]. In teleoperation and VR, haptic feedback improves task success, accuracy, and completion times. As meta-analytical studies show, force feedback significantly enhances task performance by reducing applied forces and completion times. While vibrotactile feedback benefits task performance, its effects are generally lower than force feedback. Nonetheless, both force and vibrotactile feedback help avoid exaggerated force levels and contribute to success in various experimental tasks [22]. Incorporating force feedback and vibrotactile sensing into robotic systems will provide valuable insights into the construction process, enabling a deeper understanding of the tasks performed by the robot.

VR simulations offer significant cost savings and sustainability advantages in construction projects. By reducing the need for physical prototypes and minimizing material waste, virtual simulations contribute to overall project cost reduction and environmental conservation.
Several challenges still hinder the role of simulation in robotics. The advancement of simulation in robotics depends on initiating a cross-disciplinary exchange between robotics and simulation, transitioning from academic discourse to practical technology development [23].

III. FRAMEWORK

Fig. 1 explains the framework followed. The researchers observed a human worker's welding procedure. They also model the humanoid's performance in VR by mimicking the human. VR enables model locomotion in a reliable outdoor environment and design to external disturbances, different terrains (construction floor morphology), and payloads with various mass variations. The simulations visually represent the humanoid's gradual gait changes based on locomotion and the requirements for rapid adaptation to sudden errors (obstacles). The researchers simulated the process for humans and robots while considering typical constraints. Then, they analyzed the production rate, the utilization rate of the equipment, the queuing time, and the average total time of the task.

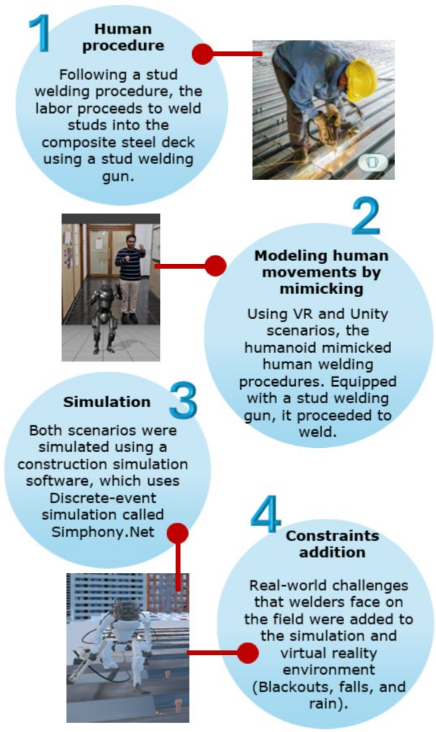

Fig. 1. Framework

IV. USE CASE

For this analysis, a simulation using SIMPHONY.NET [24] was conducted on a specific construction process – welding shear studs in a composite floor as a connector between the steel beam and the concrete of the floor slab. This task was chosen due to its repetitive and cyclical nature. The software was first used to simulate how a human worker performs this task. The scenario includes welding, removing the ferrule, and conducting quality tests every 10 studs, according to the American Welding Society (AWS) standards.

As a second step, the welding process was computed in a virtual reality scenario as if a humanoid were performing the task (see Fig. 2). The researchers utilized Unity software to develop a construction environment scene for a stud welding scenario. A rooftop setting was created to develop a construction environment scene in Unity for a stud welding scenario.

Challenge (Category)	Definition	Solution	Lesson Learned
Model rigging. (Robotic Motion)	Rigging, in the context of computer graphics and animation, refers to the process of adding a digital skeleton to a 3D model. This skeleton, composed of interconnected bones or joints, allows the model to be manipulated in a flexible and realistic manner.	Using blender modes like Object, Edit, and Pose. Rigging involved creating an armature for precise movement control. Rigify add-on expedited rig generation, customizable to Atlas' complexity. Inverse kinematics and forward kinematics techniques enabled natural motion control.	The rigging process emphasized the importance of meticulous planning, to achieve successful outcomes in 3D animation and simulation projects.
Scene setup (Spatial Accuracy & Planning)	A scene refers to a self-contained environment where game objects, assets, and other elements are arranged and interact to create a specific visual presentation. Within a scene, developers can place and manipulate objects, apply physics, lighting, and audio effects, and script behaviors to create dynamic and interactive experiences for users	Creating a suitable scene requires consideration of environmental factors and adherence to OSHA. Extensive efforts were invested in integrating realistic scenery, construction elements, background audio, and worker motion to ensure authenticity in the simulation environment.	Thorough consideration of environmental factors and adherence to safety regulations were crucial in creating authentic simulation environments. Extensive planning is required.

TABLE 1. IMPLEMENTATION CHALLENGES FOR HUMANOID SIMULATIONS

Next, the stud welding process was incorporated into the scene, and the humanoid robot was modeled to simulate the stud welding process. The robot is programmed to move and perform the welding task realistically.

Navigating the intricacies of developing a simulation environment presents many challenges, requiring a delicate balance between technical expertise and creative problem-solving. Table 1 displays the challenges faced and the solutions.

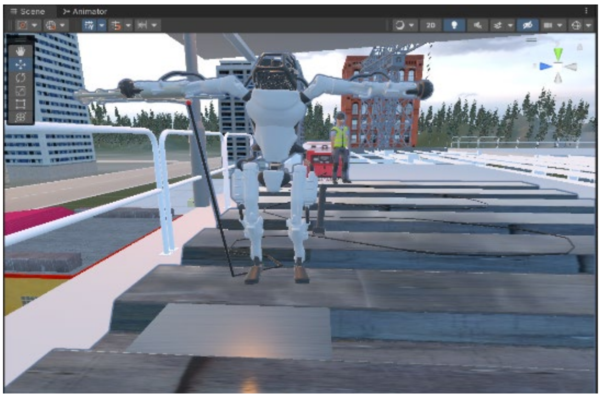

Fig. 2. Atlas Humanoid with a stud welding gun

Using this VR scenario, the researchers returned to SIMPHONY to conduct the simulation again, considering that the robot was performing the task. The results were obtained for both humans and robots. However, this first simulation was input in a scenario where everything flows smoothly without constraints or obstacles. For a more realistic approach, researchers must consider a series of obstacles, limitations, and circumstances a human welder can face while welding. Recall that the aim is to understand the challenges of effective robotic operation in tackling obstacles and cluttered workspaces and accounting for uncertainty arising from dynamic environmental changes. It is imperative to consider these to obtain more realistic production rates and total process time to simulate the robot and human welder. Some of these tasks are easily fixed by a human, such as refilling a gas tank, but a robot needs to be trained to react to these challenges, which go above and beyond the simple welding assignment.

The researchers considered three typical issues that the welding laborer or humanoid may face in the field: rain as an external condition, blackouts due to malfunction of the engine driver welder (ranger), and tripping over the cable while walking, which can also lead to disconnecting the power supply unintentionally. In this paper, the researchers will only present results for the best-case scenario (no constraints) and worst-case scenario (tripping on the cable and leading to a blackout). Fig. 3 exemplifies the worst-case scenario simulation using conditional branches.

V. RESULTS

The statistical report provides the production rate per second and the total process time of the two scenarios, allowing stakeholders to verify if the process aligns with the project budget, schedule, and specifications. the comparison results can be found in Table 2.

TABLE 2. SIMULATION OUTCOMES ACROSS SCENARIOS

	Human	Robot (best-case)	Robot (worst-case)
Total process time (mins)	5.6	4.05	8.13
Production rate (studs/min)	6.78	9.36	4.6

There is a difference between the simulation time and the production rate between the robot and the human since the time of the tasks for the robot is constant, while the human time for tasks is variable. This is the case for several reasons. First, the robot is less likely to incur errors or delays, such as dropping a stud. Second, humans are likely to take quick breaks due to exhaustion or get distracted while talking with other laborers, among other distractions. Finally, the quality control test time might vary depending on the strength and experience of the laborer. Because of this, when simulating conditions of uncertainty in the cycle for the human laborer, the researchers varied the time it may take for the person to conduct each task; specifically, a probability triangular distribution was used, which considers both a minimum, maximum, and mode time for performing each task. A constant time was assigned to the robot simulation.

The simulation without constraints was run to show the production rate, utilization of equipment percentage, and task completion time. These were run under perfect scenarios without constraints. As mentioned above, the simulation now considers a scenario where the humanoid trips over the cable, leading to a blackout. How does this impact time and production rate? Conditional branches were incorporated into the simulation software to simulate this. Specifically, the simulation considers a "worst-case" scenario where the humanoid trips. The humanoid must untangle the cable, get up, and inform a laborer to reconnect the power supply.

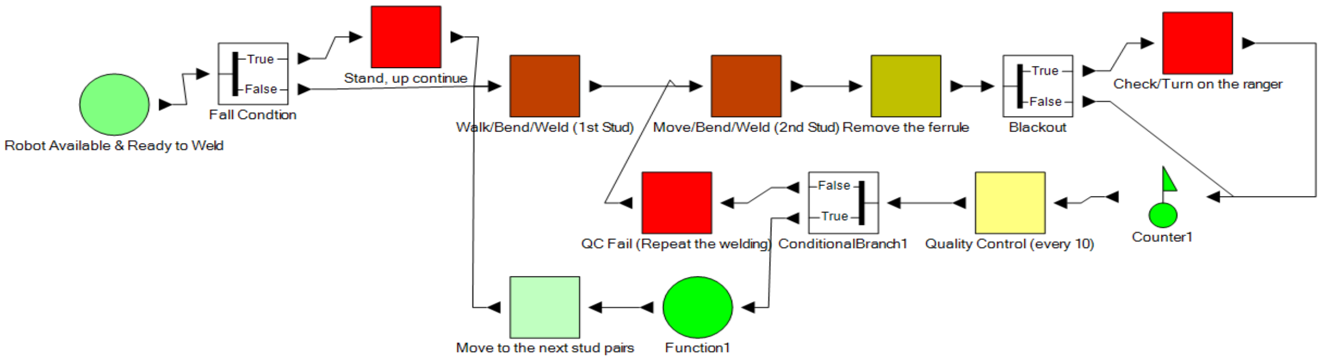

Fig. 3. Worst-Case Scenario Robot SIMPHONY Simulation

It must be re-weld due to a quality control test failure. As seen in Table 2, this almost doubles the total process time and significantly reduces the production rate, but it conveys a more realistic scenario.

VI. Conclusion

Humanoids' implementations in the construction industry face significant challenges. Unstructured environments present unpredictable conditions for navigation, object recognition, and decision-making, among other factors. The researchers illustrate some uncertain conditions (mobility and balance, dexterous manipulations, mechanical robustness to environmental conditions) by comparing human and humanoid welder tasks in simulations. This work advances the understanding of humanoids' adaptability for construction tasks analogous to humans. It is a step towards formulating frameworks for a new embodied way of future robotic designs.

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