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TOWARD SPATIAL AND COGNITIVE HUMAN-ROBOT INTERACTION: A GAME-BASED SIMULATION FOR CONCRETE 3D PRINTING IN CONSTRUCTION

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Abstract

Robotic systems are increasingly present on construction sites, introducing new challenges related to safety, spatial coordination, cognitive workload, and worker stress. This paper takes initial steps toward understanding both the spatial and cognitive dimensions of human proximity behavior within human-robot interaction (HRI), particularly focusing on how concrete 3D printing robots affect work execution, mental load, and worker comfort. An interactive simulation game was developed to model realistic scenarios of a worker navigating around a concrete 3D printer. Four key scenarios were designed to reflect common on-site challenges: (1) selecting work locations near or far from the robot, (2) navigating obstructed paths, (3) working near social distractions, and (4) responding to erratic robot behavior. The game is designed to collect data on task execution time, proximity to the robot, as well as subjective cognitive load indicators using integrated questionnaires. This controlled, repeatable environment offers a safe way to study human-robot proxemics and cognition in goal-oriented construction settings. By identifying patterns of high-risk interaction and elevated mental effort, this study lays the groundwork for developing responsive, human-aware robotic systems that improve safety, comfort, and productivity in shared construction workspaces.

Keywords: construction, human-robot interaction, proxemics, cognitive workload, serious games.

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1. Introduction

As construction sites evolve through the integration of intelligent robotic systems, understanding how human workers adapt behaviorally to these technologies is an important issue to address. With the rise of technology in the field, adoption of mobile and autonomous robots for tasks like concrete printing, site monitoring, and material handling, etc. is getting popular. These machines are expected to operate in close proximity to human workers. However, construction environments are inherently dynamic, spatially constrained, and socially complex, making the introduction of robots a potential source of disruption for humans. Workers must navigate not only physical obstacles but also psychological demands such as stress and cognitive load, which can be intensified by unpredictable robot behaviors. One key aspect of this challenge is "proxemics", the study of personal space and spatial behavior in social contexts. While traditional human factors research has extensively studied workload and stress in manual tasks, less attention has been given to how robot presence, movement patterns, and behavioral predictability influence human psychological states in real or construction-like environments. This gap limits the ability to design intelligent robotic systems that are truly worker-centric, in other words robots that move and behave in socially acceptable ways to ensure physical safety, mental comfort, and trust.

To begin addressing this challenge, the paper presents an exploratory, game-based simulation study in which players engage in virtual concrete reinforcement and finishing tasks near a 3D concrete-printing robot. The simulation allows for the manipulation of variables such as robot speed, proximity, and predictability, while collecting subjective (NASA-TLX) and physiological (HRV) data. Rather than drawing conclusions, the study aims to investigate how such variables may influence cognitive load and spatial behavior. This early-stage work contributes to the foundational understanding needed to inform

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the future development of adaptive human-robot systems that prioritize safety, task performance, and psychological well-being in construction settings.

2. Related Work

As robots become more integrated into construction settings, understanding how humans interact with them in shared spaces has become critical. Proxemics, the study of personal space, has emerged as a key factor in human-robot interaction (HRI). Research shows that workers tend to keep more distance from robots than from humans, especially when robots behave unpredictably or operate in tight spaces [1]. This extra spacing can increase cognitive load and hesitation, even when no real danger is present. Studies have also emphasized that robots should adhere not just to collision-free paths but also to social norms of spacing in dense, task-driven environments like construction ones [2]. To safely investigate these interactions, researchers have turned to simulations, virtual reality (VR), and gaming. Unity-based simulations have helped model human navigation around robots and identified patterns in avoidance and spatial tension [1]. Although some studies measure physiological responses to robot behavior [3], these are rare in construction contexts. However, adaptive robots that respond in real time to human proximity and physiological cues can reduce stress and improve user comfort [4].

On the other hand, efforts to measure cognitive load in HRI are growing. Tools like NASA-TLX, commonly used in construction safety research [5], have shown that unpredictable robot behavior raises mental demand and frustration in automated tasks [6]. Researchers have also called for the integration of physiological data such as heart rate variability (HRV) to complement subjective stress measures [7]. Yet, such multimodal approaches remain underutilized in construction-focused simulations. For instance, Kim et al.'s work did not assess workload, leaving open questions about the cognitive effects of robot proximity [1].

As such, this exploratory study seeks to address these gaps by proposing the integration of scenario-based simulation with behavioral, physiological, and self-reported workload data. It also aims to explore the use of machine learning to detect behavioral patterns without relying on preset stress thresholds. This holistic approach has the potential to inform the design of cognitively and physically considerate robots, ultimately supporting safer and more comfortable construction environments.

3. Methodology

3.1 Study Design and Objective

This exploratory study investigates human proximity behavior and cognitive responses in human-robot interaction (HRI) in construction environments. Players engage within a game-based simulation where they perform common construction tasks such as installing reinforcing bars and finishing surfaces near a virtual robotic concrete 3D printer. The simulation is designed to reflect realistic on-site challenges and spatial interactions in a safe, controlled, and repeatable manner, thereby allowing for flexible testing of various interaction scenarios.

3.2 Simulation Environment Development

The interactive game-based simulation was developed using Unity, replicating typical construction tasks performed alongside a concrete 3D printing robot (Fig. 1). It models key aspects of human-robot collaboration in a virtual construction environment.

Fig. 1. Unity simulation environment.

Within the gaming environment, two interaction modes are implemented:

- Scenario-based tasks: Players select actions via a simple interface, allowing study of decision-making in controlled settings, ideal for users with limited computer experience.
- Free-movement tasks: Players navigate freely in the environment, providing continuous spatial and behavioral data.

More specifically, four primary scenario categories assess worker behavior under varied HRI conditions (Fig.2):

- Proximity scenarios: Objects are positioned at varying distances from the robot's path, encouraging players to make spatial decisions based on perceived safety or efficiency. The robot's proximity dynamically changes in real time to explore how players respond and adapt their positioning.
- Behavioral predictability: The robot moves either predictably or exhibits erratic stops and direction changes to simulate uncertainty.
- Environmental context: Scenarios take place in both indoor and outdoor settings to explore spatial perception variations.
- Social interference: NPCs placed near the task zone introduce social distractions affecting worker navigation and interaction.

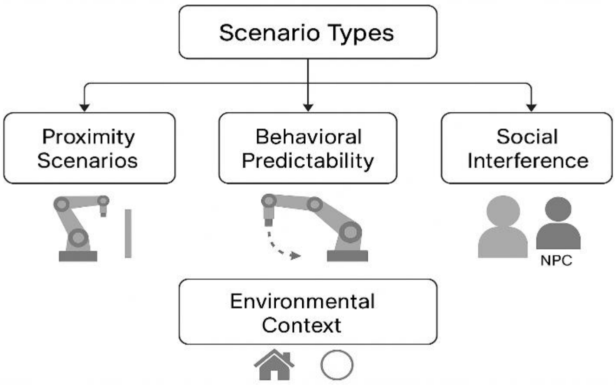

Fig. 2. Four scenarios categories tested in the simulation

Fig. 3 depicts four potential simulation scenarios.

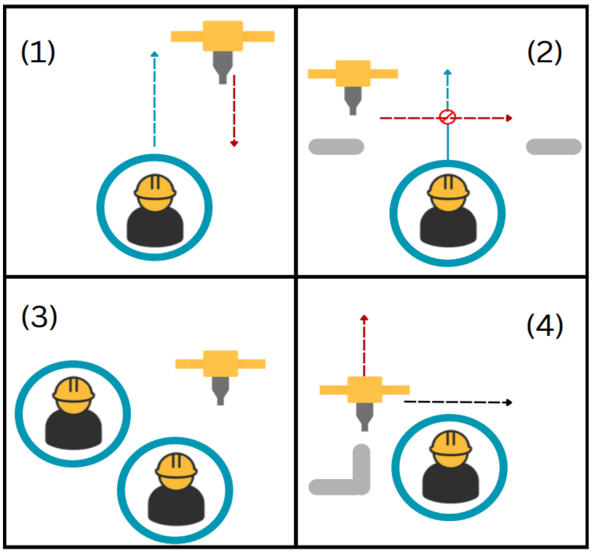

Fig. 3. Visual representations of four simulation scenarios: (1) Task selection near vs. far from the printer, (2) Obstructed path with moving printer, (3) Social distraction during printing, and (4) Unpredictable printer behavior

3.3 Data Collection Strategy

A multimodal data collection strategy is proposed. Specifically, physiological data such as Heart Rate Variability (HRV) may be monitored to explore potential indicators of stress. Behavioral data may also be collected, including metrics like task completion time, proximity to the robot, route choices, and action selection patterns. Additionally, subjective data could be gathered through a customized NASA-TLX questionnaire interface integrated into the virtual environment (Fig. 4), allowing for in-context assessment of perceived workload (e.g., mental demand, effort, and frustration) immediately after each task scenario. This design aims to support contextual data collection while minimizing disruption to the immersive experience.

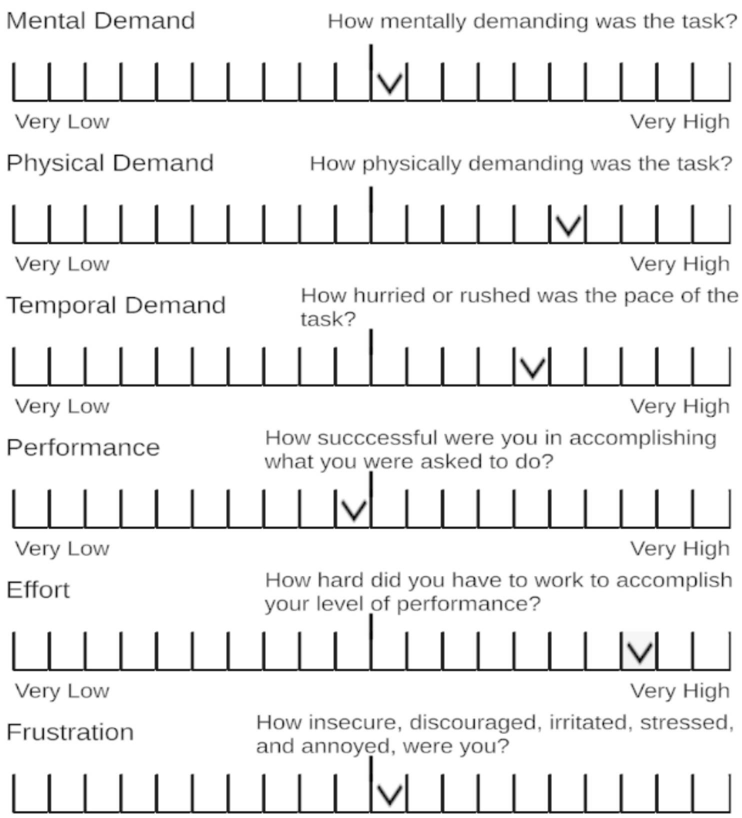

Fig. 4. NASA-TLX survey presented within the simulation.

3.4 Planned Data Analysis

Collected data will be analyzed to identify patterns in spatial behavior and cognitive load as influenced by robot proximity, behavior predictability, environmental context, and social distractions. The study aims to examine how these factors affect worker safety, comfort, and performance. More specifically, this includes (1) assessing spatial behavior patterns such as route selection and task execution in relation to the robot's position and movement, and (2) giving special attention to contextual factors that influence human-robot proxemics, including environment type, the presence of non-player characters (NPCs), and perceived robot intent. In addition, Multimodal data (HRV, NASA-TLX, spatial metrics) will be used to train machine learning models to predict task strain and inform adaptive robot control strategies for real-time adjustment based on human state. In other words, these models will provide insights into how robot behavior affects workers' cognitive and physiological states and whether real-time behavioral adjustments are necessary.

4. Study Exploratory Nature and Limitations

This study serves as an initial exploratory investigation into human-robot interaction proxemics and potential cognitive effects within a simulated construction environment. Results are not yet available and will be presented in future work following participant testing and data analysis. Furthermore, while the game-based simulation provides a controlled, repeatable platform to examine spatial behavior and cognitive workload, several limitations should be noted:

- Simulation Constraints: The virtual environment does not fully replicate the physical, sensory, and emotional complexity of actual construction sites. Factors such as fatigue, noise, temperature, and unpredictable real-world hazards are not modeled, which may affect in-situ worker stress and behavior.
- Physiological Measures: Although HRV offers valuable insights into stress, its sensitivity to physical motion and environmental conditions limits its reliability within the simulation context. Greater control or complementary measures may be needed in future work.
- Data Generalizability: Machine learning models trained on simulated data may not directly translate to real-world applications without further validation and tuning using data from actual construction workers and settings.
- Scenario Diversity: The current set of experimental scenarios represents a limited subset of the broad range of interactions found on construction sites. Expanding scenario variety and incorporating diverse worker profiles will be important to enhance representativeness.

Despite these limitations, the study's exploratory design offers a starting point for understanding proxemic-aware and cognitively considerate human-robot interaction in construction contexts. It aims to lay the groundwork for future research focused on developing adaptive, worker-centered robotic systems that can enhance cognitive well-being, safety, comfort, and efficiency in shared workspaces.

7. Conclusion and Future Work

This study takes initial, exploratory steps toward understanding the psychological and cognitive effects of working near a robotic concrete 3D printer within a simulated construction environment. It examines how robot behavior variables such as speed, predictability, and proximity influence workers' stress levels, perceived workload, flow state, and spatial interaction. The overarching goal is to inform the design of collaborative human-robot systems that enhance safety, comfort, and efficiency on construction sites.

The developed game-based simulation provides a controlled, repeatable platform for studying human behavior in construction-specific, task-oriented scenarios. Building upon existing human-robot proxemics research, this work emphasizes goal-directed interactions in realistic concrete reinforcement and finishing tasks. By integrating real-time behavioral data, proximity tracking, and subjective workload measures (i.e. NASA-TLX data), the system lays groundwork for future adaptive robotic control strategies that can dynamically respond to human stress and spatial preferences.

Future research will focus on empirical studies involving construction workers in real-world settings, uncovering behavioral patterns through machine learning, and applying reinforcement learning techniques to enable robots to adjust their behavior dynamically based on human state indicators. Ultimately, this research aims to deepen understanding of human proximity behavior in human-robot interaction (HRI) within construction environments and contribute to the design of intelligent, worker-centered construction robots that foster safety, trust, and productivity in shared workspaces.

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