VR Embodied Robot System: A Preliminary Validation of a Novel Approach to Investigate Crowd Crush

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Abstract

The increasing frequency of large-scale public events has heightened the risk of crowd crush incidents, which present significant public safety challenges. Despite advances in research on crowd behavior, existing methods, including purely virtual simulations, bear fundamental limitations in capturing the critical physical dynamics — such as contact forces and inertia — that govern high-density interactions. This study proposes a novel virtual reality (VR) embodied robot system as a preliminary experimental platform for future research on crowd dynamics and crowd-crush-related physical interactions. The system introduces behavioral heterogeneity by allowing users to teleoperate robots in VR, thereby injecting human intentions into a system constrained by real-world physics. Compared to existing swarm robots, the design incorporates an inverted pendulum model; its dynamic instability functionally mimics the human need to actively maintain balance, providing a more realistic simulation of physical contact under external forces than statically stable robots. We conducted user experiments involving ten participants to evaluate system performance, usability, and user experience. The system achieved a stable frame rate and low network latency, ensuring real-time interactions. User feedback indicated good usability and no significant discomfort or simulator sickness. The present study validates the platform's technical feasibility, real-time performance, and usability in a controlled low-density scenario. While the current experiment does not reproduce collective crowd-crush phenomena, it establishes a foundation for future high-density studies with sensor-equipped robots. Such future work may enable the simultaneous collection of human behavioral data (via VR teleoperation) and physical interaction data (through robotic entities), thereby supporting more realistic investigations of crowd dynamics under constrained and high-density conditions.

Keywords –

Virtual reality, Robot swarm, Crowd crush

1 Introduction

With rapid urbanization and global population growth, large-scale public events have become more frequent, increasing the risk of crowd crush incidents [1]. These events, often associated with religious, entertainment, festival, or sports gatherings, pose significant public safety challenges [2]. Historically, crowd crushes have resulted in numerous injuries and fatalities, underscoring the need for a deeper understanding of the mechanisms underlying crowd crush incidents [3]. Research on crowd disaster has focused on various aspects, including pedestrian dynamics, human behavior, and psychology. Previous studies explored crowd behavior or dynamics at different stages—low density, high density, and trampling—using a range of research methods such as simulations, field studies and virtual reality (VR) based experiments.

Simulation studies play a crucial role in understanding the evolution and management of crowd crushes. For instance, Helbing et al. [4] used simulation to model crowd evacuation dynamics during panic, concluding that a hybrid strategy combining individual and collective behaviors is optimal in emergency situations. Field experiments and VR behavioral experiments further elucidate the mechanisms of crowd movement. For instance, Garcimartín et al. [5] investigated how obstacles impact pedestrian flow during crowd evacuations. Their study suggested that obstacles do not always improve evacuation efficiency and can sometimes reduce the risk of falls by mitigating lateral impacts. Psychological investigations have provided additional insights into crowd behavior. Sieben & Seyfried [6]analyzed eyewitness accounts from the 2010 Love Parade disaster, highlighting the coexistence of cooperation and competition in life-threatening crowds, with panic not being the primary cause of the disaster.

However, despite these advances, current research methods have notable limitations that hinder a deeper understanding of crowd crush dynamics. Field and VR behavioral experiments are often conducted in simplified environments, such as evacuating a building through narrow exits [4], [7], due to ethical concerns, including the risk of physical harm and psychological distress to participants. These constraints prevent the simulation of high-density or extreme crowd scenarios, which are critical for capturing key behavioral and physical interactions, such as crowd pressure. Specifically, while VR-based behavioral studies solve these ethical issues, they introduce a different, critical limitation: the absence of genuine physical consequences. In a purely virtual environment, avatars lack mass, inertia, and the physical constraints of a shared space. They cannot replicate the involuntary, physics-driven phenomena-such as contact forces, pressure waves, and force chains-that are the true mechanisms of a crowd crush. As a result, our understanding of the underlying mechanisms of crowd crush incidents remains limited, and the validation of existing simulation models is hindered. Additionally, while psychological studies offer valuable insights, they often rely on limited data, which restricts their ability to fully represent the evolution of crowd crush.

Latest advancements in robotics offer a promising solution to the limitations outlined above. Swarm robotic systems have been recognized for their potential in studying human behavior. For instance, Dorigo et al. [8] suggested that robot swarms can help explore collective intelligence and crowd dynamics, providing insights into human social behavior. Most current swarm systems, however, operate as particle-based models, in which large numbers of homogeneous, relatively simple robots collectively produce emergent behavior. For instance, Rubenstein et al. [9] proposed a cost-effective, scalable system that allows researchers to test collective algorithms across large robot swarms. While this design is effective for coordination, it fails to capture individual differences and role heterogeneity, making it unsuitable for studying human behavior [8]. To address this drawback, we propose that swarm robots intended for human behavior research should reflect individual role differences within the group.

Dafarra et al. [10] introduced the concept of remote embodiment, where human operators teleoperate robots from a first-person perspective, thus capturing more genuine behavioral responses. Building on their work, we further integrate immersive VR to heighten the realism of the interaction experience for remote operators. VR creates an authentic disaster environment [11], [12], while sensor data from the robots drives human virtual avatars, synchronizing their positions, postures, and movements.Together, these elements enable operators to experience a first-person perspective of a highly realistic disaster scenario with moving crowds. This approach uses the robot as a 'physical avatar' to supply the missing physical constraints (mass, inertia, collision) while leveraging VR to capture genuine, heterogeneous human behavioral responses to those constraints, all while avoiding ethical concerns.

Moreover, most current swarm robots are statically stable (e.g., 3- or 4-wheeled), making them unsuitable for simulating the physics of bipedal human balance. To address this issue, we propose to use an inverted pendulum model. The value of this model is not its visual similarity to a human, but its functional similarity. A self-balancing robot, like a standing human, is an inherently unstable system that must continuously make dynamic adjustments to maintain equilibrium. This property is crucial for simulating realistic physical interactions, as the robot's response to an external push is not static friction but a dynamic balancing action. This allows for a more accurate representation of how forces propagate through a high-density crowd.

The objectives of this study are twofold: (1) to develop a VR-embodied robot swarm platform that integrates human teleoperation with real-world physical constraints for crowd dynamics research, and (2) to conduct a preliminary validation of the system's technical performance (e.g., latency, stability) and usability (e.g., simulator sickness, user experience) in a simple controlled scenario, thereby establishing its feasibility for future high-density crowd-crush-related studies.

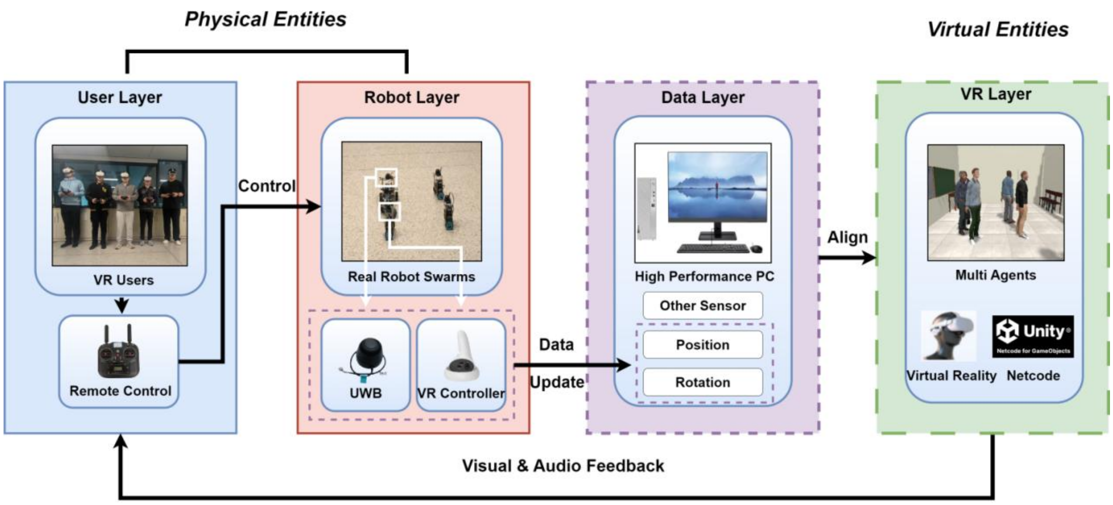

Figure 1. VR embodied robot swarm system architecture

2 VR Embodied Robot Swarm System

We propose a novel VR-embodied robot swarm system that combines human embodiment with functional dynamic modeling to create a new experimental platform for studying crowd dynamics under physically constrained conditions. By allowing users to teleoperate the robots, the system introduces behavioral heterogeneity, while the dynamically-balancing robots, based on the inverted pendulum model, aim to replicate the physical constraints and reactive balancing of human contact dynamics. VR creates an immersive, ecologically valid context for studying crowd behavior. These core elements are further detailed in Sections 2.1 and 2.2.

2.1 System Design

As shown in Fig. 1, we reference the 5-Dimension Cross-Industry Digital Twin Applications Model proposed by Newrzella et al. [14], focusing on the development of a new research paradigm in the field of crowd disaster studies. This model explores the scope and features of physical entities, forms of data communication, and the scope of virtual entities. The entire system is divided into four layers: 1) the User Layer, 2) the Robot Layer, 3) the Data Layer, and 4) the VR Layer.

First, in the User Layer, users wear VR headsets, such as the Meta Quest2/3, experiencing the movement of a virtual avatar from a first-person perspective. The user operates a HOTRC remote controller, model HT-8A, operating in the 2.4GHz ISM band with 8 channels, for forward/backward, left/right movements, and rotations. This controller employs Frequency-Hopping Spread Spectrum (FHSS) technology, which helps reduce interference between devices, allowing multiple controllers to coexist within the same frequency band without interference. The use of a joystick to control the virtual character's movements in disaster scenarios has been widely adopted in human behavior studies in such contexts [15], [16]. This setup aims to achieve human-like embodiment, allowing the user to not only experience the robot's movements in an immersive way but also to control their respective robot's behavior within the swarm, effectively reproducing human actions in the virtual environment.

In the Robot Layer, we use Nooploop's Ultra-Wideband (UWB) positioning system to track the robots' positions and collect and organize the position data. The positioning data of the balance cars is calculated by the UWB base station, which computes the positions of the UWB nodes on each vehicle and sends the data to the high-performance PC. For rotation data, we propose a novel integration by mounting a standard virtual reality (VR) controller onto the robots. The rotation data is presented in quaternion form. The VR controller uses an Inertial Measurement Unit (IMU) sensor, data fusion algorithms, and optical tracking to process rotational data, achieving high-precision direction estimation and correction.

In the Data Layer, position and rotation data from the robots are received, processed, and synchronized for use in the VR environment. This layer enables dynamic updating of robot trajectories, real-time tracking and visualization of target positions, and flexible adjustment of the display range, thereby improving data usability and system robustness.

In the VR Layer, we built a multi VR platform using Unity Netcode [17]. This platform can obtain the position and rotation of all robots in real-time from the Data Layer and synchronize the data over a local area network (LAN). The platform synchronizes each robot's position and rotational data to the VR avatar, ensuring that each virtual avatar in the virtual environment accurately reflects the dynamics of its corresponding robot in the real world.

The entire system uses UWB positioning, VR controllers, and data synchronization technologies to transmit the robot swarm's position and direction data in real-time to the Data Layer, which is ultimately presented to the VR user, forming a complete closed-loop system. This enables users to remotely control their individual robot from a first-person perspective, where their actions directly affect the behavior of that robot, providing immediate feedback on its motion status.

2.2 Robot Design

2.2.1 Robot Architecture

The robot's design is based on the functional requirement of mimicking human balancing dynamics using a two-wheeled balancing system, modeled as an inverted pendulum. We develop on the basis of the Wheeltec B585 balancing robot. Our robot is equipped with an STM32 F103RCT6 microcontroller board (STM32) as the lower-level controller and a Lubancat development board as the host computer. The Lubancat board is equipped with an RK3588 processor, 8GB of RAM, and 64GB of storage, and supports Ethernet, USB 2.0/3.0 interfaces, and a Mini-PCIe interface for expansion via WiFi or 4G modules. A UWB sensor is used to collect position data, powered by the host computer, while a VR controller mounted on the robot captures rotation data. Additionally, a frequency-matching device interfaces with the remote control unit to ensure precise control.

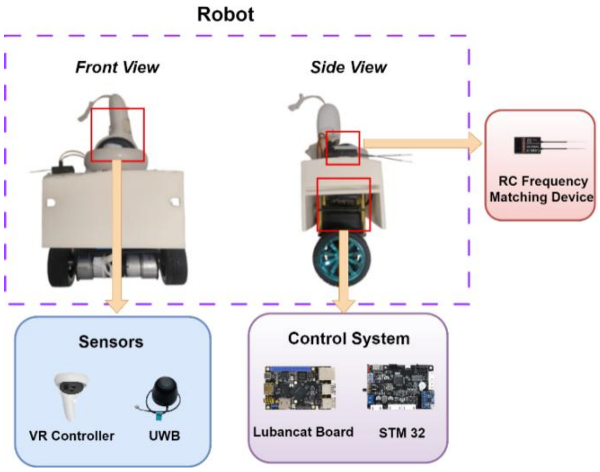

Figure 2. Robot component architecture

Table 1. System specifications of the VR-embodied robot platform

Item	Specification
Robot	Wheeltec B585 self-balancing robot
Robot dimensions	184.2 × 74.2 × 151.9 mm
Robot mass	1.1 kg
Low-level controller	STM32 F103RCT6
Host computer	Lubancat (RK3588, 8 GB RAM, 64 GB storage)
Position tracking	Nooploop UWB
UWB positioning accuracy	5 cm
Tested arena size	3.9 m × 2.4 m
Maximum number of robots tested	2
Rotation tracking	mounted VR controller
Control architecture	cascaded PID
VR headset	Meta series
VR platform	Unity netcode

2.2.2 Circuit Design

As shown in Fig. 3, the robot's control circuit integrates key components: the microcontroller system, which integrates sensor data, executes control algorithms, and coordinates the operation of connected modules; multiple serial communication ports for seamless data exchange with external devices, including Serial Port 1 (host computer), Serial Port 3 (remote control), and Serial Port 4 (UWB device for positioning); the power supply system, which provides voltage to all modules; and the motor drive circuit, which generates pulse width modulation (PWM) signals via Timer 1 of the STM32 to control motor speed and direction. The encoder feedback system, utilizing Timers 2 and 4, ensures real-time motor speed feedback for precise control.

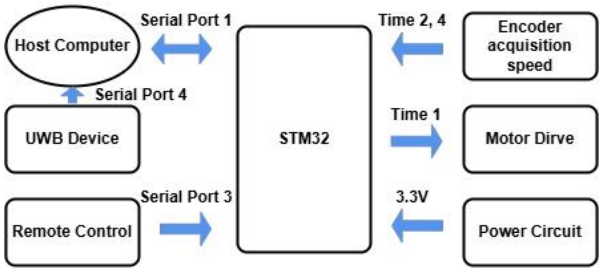

Figure 3. Robot circuit design

2.2.3 Dynamical Modeling and Control

The control objective is to provide a stable and responsive platform for teleoperation rather than a novel robotics contribution. The robot is a standard two-wheeled self-balancing system (inverted pendulum), whose inherent dynamic instability is intentionally retained to functionally mimic human balance regulation under external perturbations.

$$u_{upright} = K_{p,\theta}(\theta_{ref} - \theta) + K_{i,\theta}\int(\theta_{ref} - \theta)\,dt + K_{d,\theta}(\dot{\theta}_{ref} - \dot{\theta}) \quad (1)$$

where θ_{ref} is the desired tilt angle (usually zero), $K_{p,\theta}$, $K_{d,\theta}$ and $K_{i,\theta}$ are the proportional, derivative and gains, and $\dot{\theta}_{\mathrm{ref}}$ is the desired angular velocity (usually zero).

We adopt a conventional cascaded architecture: an inner PID loop stabilizes the pitch angle using IMU feedback; an outer PI speed loop regulates forward velocity by generating a pitch reference; and a PD steering loop outputs differential wheel commands to achieve yaw control. Gains were tuned empirically to ensure robust balance recovery and smooth velocity/heading tracking during multi-robot interactions.

3 User Experiment & Results

3.1 Experiment Design

To validate the system in terms of user experience and system performance, we conducted an experiment based on a classic pedestrian dynamics scenario, where individuals walk toward each other in a corridor [18]. This scenario has been extensively investigated in both field and VR experiments to study the avoidance behavior. We selected it because it offers a well-established context to test the system's functionality and observe if the platform can successfully capture basic human behaviors, such as avoidance, which can be analyzed in future, larger-scale studies. This scenario was not intended to reproduce crowd-crush conditions, but rather to provide a simple first-step validation of system operability, embodied interaction, and the capture of basic avoidance behavior.

As shown in Fig. 4, we recreated a classic crowd dynamics scenario in virtual reality, where individuals walk toward each other in a corridor. In the real-world setup, the corridor measures 3.9 meters in length and 2.4 meters in width. A replica of this experimental environment was built in the virtual world.

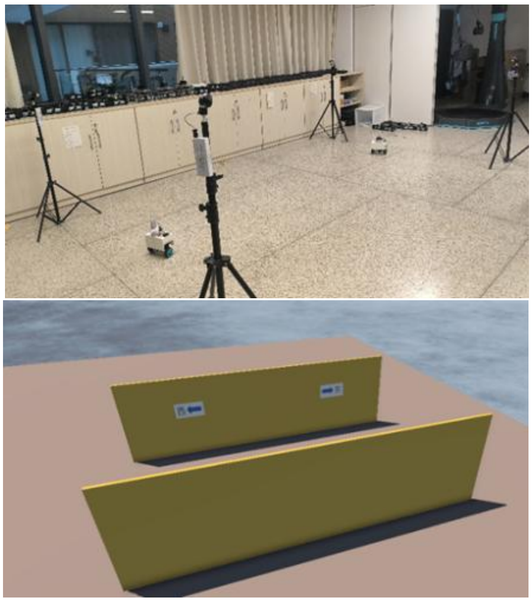

Figure 4. Experimental setup: real-world setup (upper) and virtual corridor (bottom)

The system's usability was measured by the System Usability Scale (SUS) [19]. Additionally, we used the Simulator Sickness Questionnaire (SSQ) [20] to assess the level of simulator-induced motion sickness. The user's sense of agency was measured through the Virtual Embodiment Questionnaire (VEQ) [21], specifically the section that assesses agency over a virtual body. The participants' emotional response was assessed using the Positive Affect and Negative Affect Scale (PANAS) [22]. We included attention-check questions to filter out invalid responses, thereby improving the validity of the collected questionnaires.

3.2 Participants

A total of ten participants were recruited for this study. The study protocol was approved by the Tsinghua University Ethics Committee (Approval No. THU-09-2023-04). The participants had an average age of 22.60 years (SD = 4.00). The participants self-reported their gender, with the sample including five males and five females. All participants had normal vision and no medical conditions that would render them unsuitable for VR-based experiments. Upon completion of the study, each participant received a compensation of 40 RMB.

3.3 Experiment Procedure

This experiment proceeded in six steps: 1) Participants arrived at the lab, received an informed consent form outlining the study's aims, data collection methods, and their right to withdraw at any time without penalty, and then signed the form. 2) A pre-test questionnaire was administered to gather demographic data, assess emotional states using the PANAS scale, and evaluate simulator sickness using the Simulator Sickness Questionnaire (SSQ). 3) Participants were briefed on the experiment, provided with VR headsets and remote controller, and instructed on their use. They were advised to remain still and look forward to minimize the risk of simulation sickness. 4) Participants then completed a training task, wearing VR headsets and practicing movement within the virtual environment until they were comfortable with the controls. 5) For this simple task, two participants entered the virtual scene together, positioned at opposite ends of a corridor (east and west), and were instructed to walk toward each other from the two ends. 6) After removing their headsets, participants completed a post-test questionnaire, addressing their emotions, simulator sickness, and sense of agency using the VEQ. They also completed the SUS to assess system usability. Finally, the experimenter conducted an interview to gather participants' feedback on their experimental experience and suggestions for improving the process and the experimental platform.

3.4 Platform Performance Results

The performance of the developed VR embodied robot swarm system was evaluated while the system was actively operating, and key statistics were recorded. The performance metrics, including frame rate, CPU processing time, and round-trip time (RTT), are critical for evaluating the VR embodied robot swarm system. Frame rate and CPU processing time are critical to ensure smooth rendering and responsiveness, while round-trip time (RTT) measures network latency, which is vital for real-time synchronization and smooth interactions in a multi-user environment.

The system achieved a consistent frame rate of 152.1 FPS, with the main CPU thread processing time being 6.6 ms. This indicates highly efficient frame rendering, ensuring a smooth and responsive VR experience. The render thread required only 2.2 ms, further supporting the low latency necessary for real-time multi-user VR interactions.

The round-trip time (RTT) was measured for two VR clients in our system at 0.1-second intervals to evaluate network latency and stability over 25 s, with values consistently below 120 ms (Fig. 5). Client 1 had an average RTT of 68.28 ms (SD = 7.17 ms), while Client 2 showed 73.86 ms (SD = 7.96 ms). Both clients exhibited stable performance, with minimal fluctuations, indicating low-latency communication essential for real-time interactions.

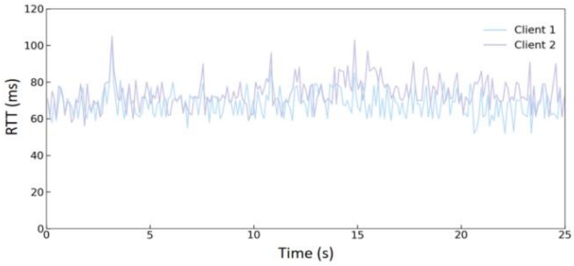

Figure 5. RTT-time relationship diagram

3.5 User Experience Results

We observed avoidance behavior in participants during the experiment, which was consistent with findings from previous studies on pedestrian dynamics [23]. Analysis of the robots' physical trajectories (collected from the UWB system) confirmed that all pairs successfully avoided collision, typically by forming lanes (e.g., both passing on the right). We measured participants' positive emotions, negative emotions, and simulation sickness before and after the experiment, with results shown in Fig. 6. Given the small sample size (N=10) and the ordinal nature of questionnaire data, we applied non-parametric tests. A Wilcoxon signed-rank test was conducted to analyze the differences in positive emotion scores between the pre-test and post-test. The results indicated no significant difference between the pre-test positive emotion score (M = 4.45, SD = 1.17) and the post-test score (M = 4.67, SD = 1.31), W = 22.0, p = 0.63.

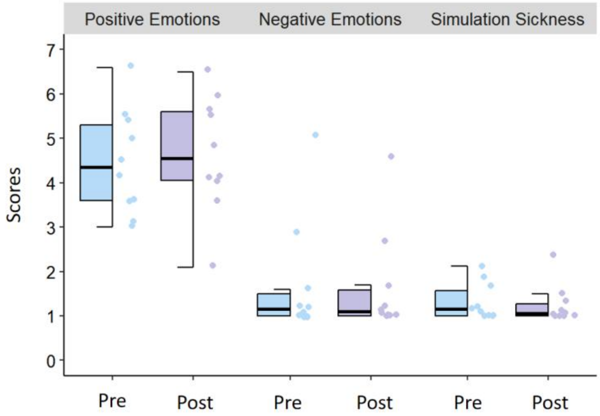

Figure 6. Participants' scores for positive emotions, negative emotions, and simulation sickness before and after the experiment

Since the data for negative emotions and simulation sickness also did not meet the assumption of normality, the Wilcoxon signed-rank test was performed. The results indicated no significant difference between the pre-test negative emotion score (M = 1.71, SD = 1.33) and the post-test score (M = 1.64, SD = 1.17), W = 8.50, Z = -0.93, p = 0.35; and no significant difference between the pre-test simulation sickness score (M = 1.32, SD = 0.42) and the post-test score (M = 1.24, SD = 0.43), W = 12.00, Z = -0.34, p = 0.73. These findings suggested that the VR embodied robot system did not cause significant emotional or physiological discomfort to users.

The SUS results are summarized in Fig. 7. The SUS score for the VR embodied robot swarm system was 68.17 (SD = 12.00), which corresponded to a 'Good' rating based on the grading system in Table 2 [24]. The system's overall usability was reflected in a mean score of 69.79 (SD = 12.55), while its learnability was represented by a mean score of 61.67 (SD = 18.92).

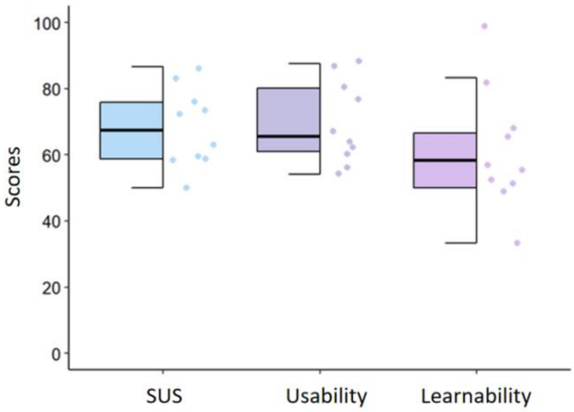

Figure 7. Scores for the System Usability Scale and its subtypes

Table 2. Qualitative grading description according to SUS scores [24]

Score	Grade	Adjective
>80.30	A	Excellent
68-80.30	B	Good
68	C	Fair

In terms of participants' sense of agency, the mean score was 5.22 (SD = 0.81) on a 7-point scale, indicating a positive level of perceived control over the virtual human body.

4 Conclusion

This paper reports a study that develops and validates the feasibility of a novel VR embodied robot swarm system. The robots are based on a functional inverted pendulum model, chosen not for visual biomimicry, but because its inherent dynamic instability functionally replicates the human need to actively balance under external forces. By leveraging human teleoperation, the system enhances robot heterogeneity, while VR improves the ecological validity of user interactions by providing a highly immersive and contextual virtual environment. A preliminary user experiment (N=10) was conducted to verify the system's technical performance and usability. The results demonstrated that the system operated smoothly, with both hardware and software functioning well, ensuring seamless user interaction. Feedback from SUS, PANAS, simulation sickness, sense of agency questionnaires, and post-experiment interviews indicated the system had good usability and did not cause significant discomfort. Overall, the system successfully met its initial design goals, proving its viability as a preliminary research platform for future crowd dynamics studies.

However, the current platform has several limitations. First, the two-wheeled self-balancing robot is only a functional approximation of human balance regulation and does not reproduce the full biomechanics of human walking, lateral stepping, or body compliance. Second, the robot's physical dimensions and contact properties differ from those of humans. Third, the current validation was conducted only in a low-density two-person corridor scenario, which cannot reproduce collective crowd-crush phenomena such as pressure waves, force chains, or turbulence. Therefore, the present study should be interpreted as a preliminary platform validation rather than a validated model of crowd-crush physics.

This platform integrates the perceptual immersion of VR with the physical constraints of robotics, such as mass, inertia, and collision. In future work, after equipping the robots with appropriate sensors, the system may enable the simultaneous collection of physical data, such as contact pressure, acceleration, and posture, together with human behavioral data via VR teleoperation. Future studies will further evaluate the suitability of this platform for investigating crowd-crush-related dynamics, including through comparisons between VR-only and VR-robot conditions. Together, these future extensions may provide a useful framework for examining crowd dynamics and informing safer crowd management strategies.

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