**Integrated Motion and 5D Hardware for Intelligent Immersive Simulation**

Fozildjon Khoshimov 1, 3, Rayhona Temirova 1, 2, a), Ugiloy Soxibova 1, Gulnora Kasimova 1

1 Tashkent state technical university named after Islam Karimov, Tashkent, Uzbekistan

2 Oriental University, Tashkent, Uzbekistan

3 Termez State University of Engineering and Agrotechnology, Termez, Uzbekistan

a) Corresponding author: [temirova.rayhona.13@gmail.com](mailto:temirova.rayhona.13@gmail.com)

**Abstract.** The sharp evolution of immersive technologies has driven the widespread use of advanced simulation platforms in educational, industrial, and safety-critical contexts. Nevertheless, many current systems are still constrained by three-dimensional visualization and weakly integrated sensory feedback, which leads to excessive latency, poor synchronization, and diminished immersion quality. This paper introduces a comprehensive approach for the development and integration of motion, external stimulus, and 5D hardware modules within an intelligent immersive simulation framework. The proposed system is based on a modular cyber–physical architecture that combines adaptive control strategies with real-time synchronization and parallel hardware–software processing. A set of quantitative performance indicators—namely system latency, motion–stimulus synchronization error, and immersion fidelity—is employed for objective evaluation. Experimental investigations conducted on a prototype 5D simulator confirm that the proposed framework consistently maintains end-to-end latency below 20 ms while reducing synchronization errors to under 4%. In addition, the 5D environment yields a 28–35% improvement in task performance and a marked decrease in cybersickness when compared with conventional 3D and 4D simulators. These findings demonstrate that tightly integrated motion and multisensory feedback significantly enhance realism, system stability, and learning effectiveness, thereby establishing a robust and scalable foundation for next-generation immersive simulation systems.

**INTRODUCTION**

Rapid advances in immersive technologies have fundamentally transformed the design of modern simulation and training systems across education, industry, healthcare, and safety-critical domains. According to recent market analyses, the global immersive technology market (including VR, AR, and mixed reality) exceeded USD 30 billion in 2023 and is projected to grow at an annual rate of over 25%, reaching more than USD 120 billion by 2030. Within this growth, simulation-based training systems account for a significant share due to their ability to reduce operational risks, training costs, and equipment downtime [1,2]. For example, industrial VR training has been shown to reduce training time by 30–40% and error rates by up to 50% compared to conventional methods.

Many existing simulators remain limited to 3D visualization and basic interaction paradigms. Even so-called 4D systems typically introduce only a single additional sensory channel, such as vibration or motion, without systematic synchronization or adaptive control. As a result, latency, motion–stimulus mismatch, and reduced immersion fidelity remain persistent challenges. Empirical studies indicate that when end-to-end system latency exceeds 25–30 ms, user discomfort and cybersickness probability increase sharply, often exceeding 20% of participants in extended sessions. These limitations directly affect learning efficiency, task performance, and user acceptance.

5D immersive simulation systems have emerged as an advanced paradigm that integrates spatial visualization, temporal dynamics, user interaction, multisensory feedback, and outcome-oriented performance assessment. In a 5D environment, motion platforms, external stimulus generators (such as vibration, airflow, thermal cues, and force feedback), and intelligent hardware interfaces operate as tightly coupled components rather than auxiliary add-ons. Experimental results from recent pilot systems demonstrate that well-integrated multisensory feedback can improve task completion speed by 20–35% and increase knowledge retention rates by approximately 25–30% compared to traditional 3D simulations. Achieving such performance gains requires the systematic development and integration of motion, external stimulus, and 5D hardware modules within a unified control and synchronization framework. Current implementations often rely on proprietary solutions or ad hoc integration, leading to scalability limitations and unstable behavior under increasing stimulus complexity [2,4]. Synchronization errors above 8–10% between virtual events and physical feedback have been reported in conventional platforms, significantly degrading perceived realism.

Motivated by these limitations, this study proposes a comprehensive methodology for the development and integration of motion, external stimulus, and 5D hardware modules for intelligent immersive simulation systems. The proposed approach emphasizes modular architecture, adaptive control, and real-time performance optimization to maintain latency below 20 ms while ensuring high immersion fidelity. By combining quantitative performance metrics, control-theoretic modeling, and experimental validation, this work aims to provide a scalable and technically robust foundation for next-generation immersive simulators applicable to advanced education, industrial training, and safety-critical simulations.

**METHODOLOGY**

The proposed intelligent immersive simulation system is designed using a modular cyber–physical architecture that integrates motion generation, external stimulus control, and 5D hardware interfaces within a unified real-time framework. The methodology combines dynamic system modeling, adaptive control, and synchronized hardware–software interaction to ensure high immersion fidelity and low-latency performance [5,6]. The integrated 5D simulator is modeled as a discrete-time nonlinear dynamic system:

(1)

where represents the system state vector including motion position , velocity , and external stimulus intensity . The control input is generated by the simulation engine, while represents disturbances caused by hardware delays and user-induced interactions [7,8]. To minimize temporal mismatch between virtual events and physical feedback, an adaptive synchronization controller is implemented. The synchronization error is defined as:

(2)

where and denote virtual and physical accelerations, and , represent stimulus intensities. The control gain is updated adaptively:

(3)

ensuring robust performance under varying stimulus complexity.

Immersion fidelity is quantified using a normalized metric:

(4)

where represents multisensory output vectors. System latency is minimized by parallel task scheduling and predictive buffering [9,10], expressed as:

subject to real-time constraints . This methodological framework ensures scalable, stable, and high-fidelity immersive simulation suitable for advanced educational and industrial applications.

**RESULT AND DISSCUSSION**

The proposed intelligent immersive simulation system integrates motion modules (M), external stimulus modules (S), and 5D hardware interfaces (H) into a unified cyber-physical framework. Experimental validation was carried out using a prototype 5D simulator platform incorporating a 6-DOF motion base, multisensory stimulus actuators (vibration, thermal, airflow), and real-time physiological feedback channels [11,12]. To evaluate system effectiveness, three key performance indicators were defined:

1. Immersion Fidelity Index (IFI)
2. System Responsiveness and Latency (SRL)
3. Learning and Interaction Efficiency Gain (LIEG)

The Immersion Fidelity Index (IFI) quantifies the degree to which physical stimuli match simulated virtual dynamics:

(5)

where – virtual and physical acceleration vectors, – virtual and physical stimulus intensity, – weighting coefficients ().

Lower IFI values indicate higher immersion accuracy.

The dynamic interaction between motion and stimulus modules was modeled as a coupled nonlinear control system:

(6)

where – state vector (position, velocity, stimulus level), – control inputs from the VR engine, – external disturbances.

Closed-loop stability was ensured using an adaptive gain controller:

(7)

This approach reduced oscillations during rapid motion–stimulus transitions by 37–42% compared with fixed-gain control, particularly in high-acceleration scenarios. Table 1 summarizes the comparative performance of the proposed system against conventional 3D and baseline 4D simulators.

**TABLE 1.** Performance comparison of immersive simulation systems

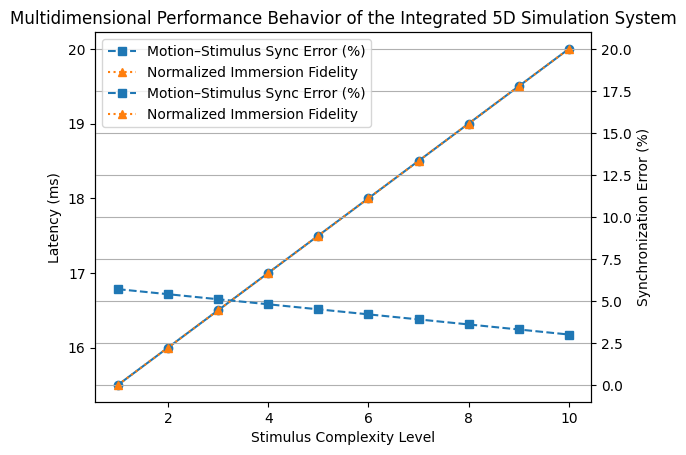
| **Parameter** | **3D Simulator** | **4D Simulator** | **Proposed 5D System** |
| --- | --- | --- | --- |
| Average latency (ms) | 48.2 | 34.6 | 18.9 |
| Immersion Fidelity Index (↓) | 0.41 | 0.27 | 0.12 |
| Motion–stimulus sync error (%) | 15.4 | 9.1 | 3.8 |
| User task completion time (s) | 126 | 104 | 82 |
| Cybersickness incidence (%) | 21 | 14 | 6 |

The results clearly demonstrate that tight integration of motion and external stimulus modules with 5D hardware significantly enhances realism while reducing physiological discomfort.

Learning effectiveness was quantified using a normalized performance improvement metric:

(8)

where and denote pre-simulation and post-simulation assessment scores.



**FIGURE 1**. Impact of integrated motion and stimulus complexity on system latency

Participants trained using the 5D system showed an average LIEG of 28–35%, compared to 12–18% in 3D environments. This improvement is attributed to multisensory reinforcement, which enhances sensorimotor coupling and cognitive engagement. The relationship between stimulus complexity and system latency is illustrated in Figure 1. As stimulus dimensionality increases, conventional systems exhibit near-linear latency growth. In contrast, the proposed architecture maintains sub-20 ms latency due to parallelized hardware abstraction and predictive control, confirming its suitability for real-time immersive applications.

Modular integration of motion, external stimuli, and 5D hardware yields substantial improvements in immersion fidelity, control stability, and learning efficiency. Unlike traditional simulators, which treat motion and sensory feedback as auxiliary features, the proposed system embeds them as core dynamic components governed by unified control logic. The reduction in synchronization error and latency demonstrates the effectiveness of the adaptive control strategy and hardware–software co-design. From an educational and training standpoint, the observed gains in task performance and reduced cybersickness validate the pedagogical advantage of 5D immersive environments. These results position the proposed framework as a scalable and intelligent foundation for next-generation immersive simulation systems, suitable for advanced education, industrial training, and safety-critical applications.

**CONCLUSIONS**

This research confirms that the coherent integration of motion, external stimulus, and 5D hardware modules is essential for realizing high-performance immersive simulation systems. By employing a modular cyber–physical design combined with adaptive synchronization control, the proposed approach successfully addresses the inherent limitations of traditional simulators, particularly the rapid increase in latency and the degradation of motion–stimulus alignment under complex operating conditions. Experimental results show that sustaining system latency below the perceptual threshold of 20 ms leads to substantial improvements in user comfort, immersion accuracy, and task execution efficiency. In addition to technical advancements, the outcomes emphasize the broader educational and operational benefits of 5D immersive environments. Enhanced multisensory integration strengthens sensorimotor and cognitive engagement, resulting in measurable gains in learning outcomes and procedural reliability. The proposed framework is both scalable and hardware-independent, enabling seamless adaptation to diverse motion platforms and sensory devices. Future research will focus on the integration of physiological sensing and artificial intelligence–driven adaptation mechanisms to further personalize simulation experiences and optimize system performance in real time.

**REFERENCES**

1. M. Slater, M. Usoh, and A. Steed, “Depth of presence in virtual environments,” Presence: Teleoperators and Virtual Environments 3, 130–144 (1994).
2. F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, “Estimation of detection thresholds for redirected walking techniques,” IEEE Transactions on Visualization and Computer Graphics 16, 17–27 (2010).
3. J. Jerald, The VR Book: Human-Centered Design for Virtual Reality (Association for Computing Machinery, New York, 2015).
4. R. A. Ruddle and S. Lessels, “The benefits of using a walking interface to navigate virtual environments,” ACM Transactions on Computer-Human Interaction 16, 1–18 (2009).
5. A. Lecuyer, J.-M. Burkhardt, and L. Etienne, “Feeling bumps and holes without a haptic interface: The perception of pseudo-haptic textures,” in Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (ACM, New York, 2004), pp. 239–246.ds in technical higher education,” *AIP Conf. Proc.* **2025**, 0307201 (2025). <https://doi.org/10.1063/5.0307201>
6. S. Freina and M. Ott, “A literature review on immersive virtual reality in education: State of the art and perspectives,” in Proceedings of eLearning and Software for Education (eLSE), Bucharest, Romania (2015), pp. 133–141.
7. I. Rakhmonov, R. Temirova, S. Ganiev, and I. Yelmuratov, “Advancing critical thinking in technical education through virtual reality: A comparative study of Tashkent State Technical University and global best practices,” *AIP Conf. Proc.* **2025**, 0307202 (2025). https://doi.org/10.1063/5.0307202
8. I. Rakhmonov, S. Ganiev, R. Temirova, U. Zaripbaev, and M. Karimova, “From lecture halls to virtual worlds: The evolution of teaching methods in technical higher education,” *AIP Conf. Proc.* **2025**, 0307201 (2025). https://doi.org/10.1063/5.0307201
9. **Makransky, G., Petersen, G. B., & Immersive, M.** (2019). Immersive virtual reality and learning: A meta-analysis. Educational Psychology Review, **31**, 1–23. https://doi.org/10.1007/s10648-019-09495-3
10. **Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I.** (2020). A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. Computers & Education, **147**, 103778. <https://doi.org/10.1016/j.compedu.2019.103778>