International Journal of Engineering & Scientific Research
Vol.14 Issue 01, January 2026
ISSN: 2347-6532 Impact Factor: 8.076
Journal Homepage: http://www.ijmra.us, Email: editorijmie@gmail.com
Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

Generative AI-Assisted Human–Machine Interfaces for Adaptive Mechatronic Decision Support Systems

Mr. Anand Shrivastava
Assistant Professor
Columbia College of Science and Commerce, Raipur (C.G.)

Abstract:

Generative Artificial Intelligence (AI) is the rapid emerging sector which works as a transformative technology. It is reshaping the design and functionality of Human–Machine Interfaces (HMIs) in modern mechatronic systems. Traditional HMIs primarily act as communication channels between operators and machines; however, the increasing complexity of industrial environments demands intelligent interfaces capable of supporting real-time decision-making and adaptive interactions. This paper studies the integration of generative AI into HMIs to create context-aware, responsive, and user-centric decision support systems. The proposed framework combines generative AI models with digital twin technology, edge computing platforms, and immersive visualization interfaces to enhance system intelligence and operational efficiency. With the continuous analysis of machine data, environmental conditions, and user behavior, the system generates predictive insights, recommend optimal actions, and dynamically adapt interface elements according to operator requirements. Such capabilities improve collaboration between humans and machines while reducing cognitive workload and minimizing the risk of operational errors. The integration of digital twins enables real-time simulation and monitoring of physical assets, allowing operators to evaluate potential outcomes before implementing decisions. Edge computing supports low-latency data processing, ensuring rapid response in time-critical applications. The proposed work also contributes to improved system resilience, predictive maintenance, and resource optimization across diverse mechatronic domains. The study highlights the important potential of generative AI-driven HMIs to advance intelligent automation. It enhances operator performance, and support sustainable industrial operations in Industry 4.0 and beyond.

Keywords:

Generative Artificial Intelligence, Human–Machine Interface (HMI), Mechatronic Systems, Decision Support Systems, Digital Twin, Edge Computing, Predictive Intelligence, Real-Time Optimization, Industry 4.0, Intelligent Automation, Adaptive Interfaces, Human–Machine Collaboration etc.

Introduction:

The rapid advancement of smart manufacturing and intelligent automation has increased the complexity of modern mechatronic workspaces. These environments involve continuous interactions among machines, sensors, software systems, and human operators, generating large volumes of data that require timely interpretation and decision-making. As industrial systems become more interconnected and dynamic, the need for advanced decision support mechanisms has become increasingly important. Effective decision support systems must optimize technical performance and consider human factors such as usability, cognitive workload, situational awareness, and operator efficiency. Traditional Human–Machine Interfaces (HMIs) primarily rely on predefined dashboards, static visualizations, and rule-based alerts. Although these interfaces provide essential operational information, they often lack the flexibility to adapt to changing environmental conditions, user preferences, and unexpected system events. As a result, operators experienced information was overload, delayed responses, and reduced decision accuracy in complex operational scenarios.

Generative Artificial Intelligence (AI) introduces a new paradigm in HMI design by enabling intelligent, adaptive, and context-aware interactions between humans and machines. Generative AI **analyzes** real-time data, understand operational contexts, generate meaningful recommendations, and simulate potential outcomes before decisions are implemented. This capability allows interfaces to dynamically personalize information presentation and decision support according to the needs and expertise of individual operators. The integration of generative AI with emerging technologies such as digital twins, edge computing, augmented reality, and predictive analytics creates opportunities for enhanced collaboration, improved operational resilience, and real-time optimization. These advancements are paving the way for next-generation mechatronic decision support systems that are more intelligent, responsive, and human-centric, supporting the evolving demands of Industry 4.0 and future smart industrial ecosystems.

Objectives of the Study:

1. To develop a generative AI-assisted Human–Machine Interface (HMI) framework for adaptive decision support in mechatronic systems.
2. To integrate digital twins, edge computing, and immersive technologies for real-time optimization and predictive decision-making.
3. To enhance operator performance, situational awareness, and ergonomic well-being through intelligent and context-aware human–machine interactions.

Literature Review:

Human–machine interfaces (HMIs) have traditionally relied on static dashboards, tactile controls, and pre-programmed feedback mechanisms. Early mechatronic systems emphasized deterministic control, where operator input was constrained by rigid interface logic. Recent advances in **adaptive HMIs** have introduced multimodal inputs (voice, gesture, haptics) and context-aware displays, enabling more intuitive collaboration between humans and machines. Grieves and Vickers [1] introduced the concept of digital twins as a foundation for adaptive HMIs, enabling real-time synchronization between physical assets and virtual models. Boschert and Rosen [2] further emphasized simulation-driven HMIs, highlighting the importance of predictive modeling in complex mechatronic systems. Generative AI has emerged as a transformative force in HMI design.

Interfaces dynamically generate recommendations, simulate scenarios, and personalize operator experiences. Zhang and Li [8] demonstrated adaptive HMIs in robotics, where generative AI improved teleoperation accuracy by simulating operator intent. Mousavi et al. [7] highlighted opportunities for generative AI in industrial DSS, noting its ability to synthesize novel solutions under uncertainty. Decision support systems (DSS) in mechatronics traditionally rely on rule-based algorithms and deterministic optimization. Fuller et al. [6] identified open challenges in DSS, including scalability, transparency, and trust. Generative AI addresses these limitations by enabling probabilistic reasoning and scenario generation.

Digital twins provide a critical foundation for generative AI-assisted HMIs. Digital twins enable predictive modeling and adaptive decision support by maintaining real-time synchronization between physical and virtual systems. Leng et al. [4] and Liu et al. [5] demonstrated how digital twins combined with generative AI enhance predictive control, ergonomic monitoring, and collaborative optimization.

Challenges in Generative AI-Assisted HMIs:

Apart from the promising advances, there several challenges in Genrative AI as given in below figure 1.1:

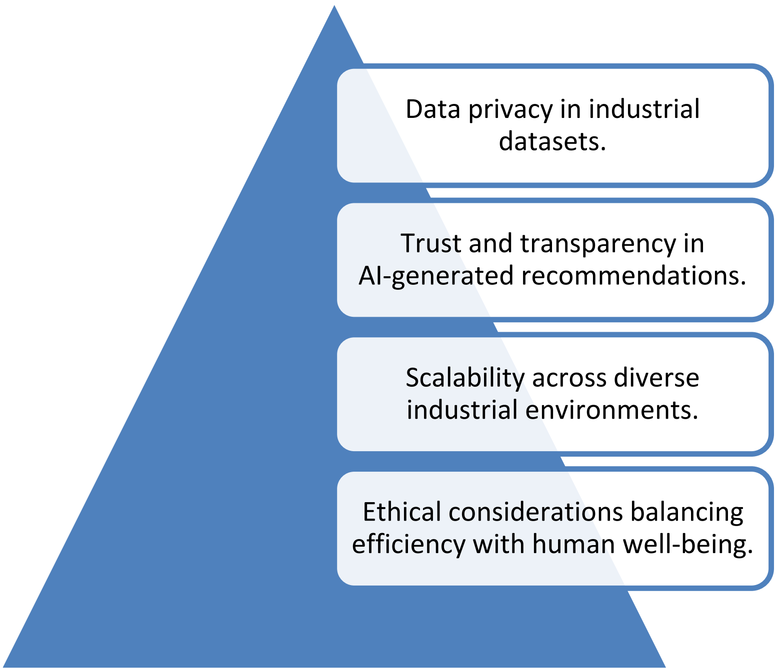

Figure 1. 1 Key Challenges and Directions in Generative AI-Assisted Human–Machine Interfaces for Mechatronic Systems

Figure 1.1 illustrates the major challenges and open research areas associated with the implementation of generative AI-assisted Human–Machine Interfaces (HMIs) in mechatronic environments. The figure highlights four critical concerns: data privacy in industrial datasets, trust and transparency in AI-generated recommendations, scalability across diverse industrial settings, and ethical considerations related to human well-being.

Proposed Architecture:

A. Generative AI Core:

The Generative AI Core serves as the intelligence layer of the proposed Human–Machine Interface (HMI) architecture. It utilizes Large Language Models (LLMs) to facilitate natural language communication between operators and machines, enabling users to interact with complex systems through conversational commands and queries. Instead of relying on traditional menus and control panels, operators obtain explanations, recommendations, and system status updates in a more intuitive manner. Generative Adversarial Networks (GANs) are employed to create realistic operational scenarios and simulate possible system behaviors under varying conditions. These simulations help operators evaluate alternative actions, identify potential risks, and make informed decisions before implementing changes in real-world environments. The AI core continuously learns from historical and real-time data, improving its ability to provide accurate and context-aware decision support.

B. Digital Twin Integration:

Digital Twin Integration forms a critical component of the proposed architecture by creating a virtual representation of physical assets, processes, and operational environments. Through continuous synchronization with sensor data and machine feedback, the digital twin accurately reflects the current state of the physical system in real time. This capability enables predictive modeling, performance analysis, and virtual testing of operational strategies without disrupting actual production processes. Digital twins help identify potential failures, optimize resource utilization, and support predictive maintenance activities by simulating future conditions and equipment behavior. Operators visualize system performance, monitor key parameters, and assess the consequences of decisions before applying them to the physical environment, thereby enhancing operational reliability and reducing downtime.

C. Edge and Cloud Computing:

The proposed architecture combines the strengths of edge computing and cloud computing to achieve efficient, scalable, and reliable decision support. Edge computing devices process a critical data near the source, such as sensors, controllers, and industrial equipment, minimizing communication delays and enabling rapid responses in time-sensitive applications. This low-latency processing is necessary for real-time monitoring, anomaly detection, and adaptive control. Meanwhile, cloud computing platforms provide extensive computational resources and storage capabilities for large-scale data analytics, machine learning model training, and long-term data management. The cloud environment facilitates collaboration across multiple locations and supports continuous improvement of AI models through centralized learning.

D. Immersive Interfaces:

Immersive interfaces enhance human–machine collaboration by incorporating Augmented Reality (AR) and Virtual Reality (VR) technologies into the decision support environment. VR environments provide realistic simulations for operator training, system testing, and scenario analysis in a safe and controlled setting. These technologies improve situational awareness by presenting relevant information in an intuitive and visually engaging manner. With the reduction the need to switch between multiple displays and information sources, immersive interfaces help minimize cognitive load, improve decision accuracy, and increase operational efficiency. As a result, operators can better understand complex system behaviors and respond more effectively to dynamic industrial conditions.

Adaptive Decision Support Mechanisms:

A. Predictive Intelligence:

Predictive intelligence is a key capability of the proposed adaptive decision support system. The system continuously monitors equipment performance and operational conditions. Historical records, environmental parameters, and machine behavior patterns are analyzed to identify early signs of potential failures or performance degradation. Instead of reacting to faults after they occur, the system proactively predicts possible issues and generates timely warnings for operators. It also recommends appropriate corrective actions, maintenance schedules, or process adjustments to prevent disruptions. This predictive capability helps reduce unplanned downtime, improve equipment reliability, enhance productivity, and lower maintenance costs. Predictive intelligence supports informed decision-making by providing operators with data-driven insights and future-oriented recommendations.

B. Ergonomic Adaptation:

Ergonomic adaptation focuses on the improvement of operator comfort, safety, and efficiency during interactions with mechatronic systems. The proposed interface continuously monitors factors such as posture, workload, fatigue levels, attention patterns, and stress indicators through wearable devices, cameras, and intelligent sensors. The system dynamically adjusts information presentation, alert frequency, display layouts, and task assignments according to the operator's current condition. For example, when high stress or fatigue is detected, the interface may simplify visual information, prioritize critical alerts, or recommend short breaks. Such adaptive behavior reduces cognitive overload and supports healthier working conditions. As a result, operators can maintain better concentration, make more accurate decisions, and perform tasks more effectively in demanding industrial environments.

C. Collaborative Optimization:

Collaborative optimization enhances cooperation between human operators and intelligent systems by establishing continuous feedback loops. Rather than replacing human expertise, AI works alongside operators to support decision-making and process improvement. The system analyzes operator inputs, preferences, and actions while simultaneously evaluating machine performance and operational constraints. Using simulation and optimization techniques, AI generate alternative strategies, compare potential outcomes, and recommend the most effective course of action. Operators review these recommendations and provide feedback, enabling the system to refine future suggestions. This collaborative approach combines human judgment, creativity, and experience with the computational power of AI. Consequently, decision quality improves, operational efficiency increases, and organizations achieve greater flexibility, adaptability, and resilience in complex mechatronic environments.

Applications:

1. Smart Manufacturing:

Smart manufacturing environments generate vast amounts of operational data from sensors, machines, and production systems. In such settings, generative AI-driven Human–Machine Interfaces (HMIs) play an important role in improving production efficiency and operational decision-making. These intelligent interfaces continuously analyze machine conditions, production schedules, quality metrics, and resource utilization patterns to recommend optimal assembly line parameters. Operators can receive real-time suggestions regarding process adjustments, machine settings, and maintenance requirements to maintain desired production levels. AI-generated simulations enable manufacturers to evaluate alternative production strategies before implementation, reducing operational risks and minimizing downtime. Generative AI-driven HMIs contribute to higher productivity, improved product quality, and enhanced manufacturing flexibility.

2. Robotics:

Robotic systems often operate in complex and dynamic environments where accurate human supervision and control are essential. Generative AI-powered adaptive interfaces improve teleoperation by providing intelligent assistance and context-aware guidance to operators. These interfaces interpret operator commands, predict intended actions, and recommend optimal robot movements based on environmental conditions and task requirements. Real-time feedback, visual analytics, and simulation-based predictions help operators make informed decisions during remote operations. Such capabilities are particularly valuable in hazardous environments, industrial automation, disaster response, and precision handling applications. With the reducing operator workload and improving situational awareness, adaptive HMIs enhance teleoperation accuracy, operational safety, and task efficiency.

3. Healthcare Mechatronics:

Healthcare mechatronic systems, particularly surgical robots and intelligent medical devices, require high levels of precision, reliability, and decision support. Generative AI-assisted HMIs enhance these systems by analyzing patient data, procedural information, and real-time surgical conditions to provide contextual recommendations to healthcare professionals. During robotic-assisted surgeries, AI assist surgeons by highlighting critical anatomical structures, predicting potential complications, and suggesting optimal procedural pathways. The integration of immersive visualization technologies further improves precision and situational awareness. These intelligent interfaces support safer and more efficient medical procedures while reducing cognitive burden on clinicians. Healthcare mechatronics benefits from improved treatment outcomes, enhanced patient safety, and greater operational effectiveness.

Challenges and Open Research:

A. Data Privacy and Security:

The effectiveness of generative AI-based decision support systems depends heavily on access to large volumes of operational and user-generated data. However, collecting, storing, and processing such information raises major concerns regarding privacy, confidentiality, and cybersecurity. Unauthorized access, data breaches, and manipulation of AI models compromise system reliability and user trust.

B. Trust and Transparency in AI-Generated Recommendations:

For generative AI systems to be widely accepted, operators must understand and trust the recommendations produced by AI models. Many advanced AI systems function as complex "black boxes," making it difficult for users to understand how specific decisions are generated. A lack of transparency lead to hesitation reduced confidence, and limited adoption in critical applications. Explainable Artificial Intelligence (XAI) techniques are therefore essential for providing clear reasoning, visual explanations, and interpretable decision pathways.

C. Scalability across Diverse Industrial Environments:

Industrial sectors differ in terms of operational requirements, infrastructure, regulations, and technological maturity. Designing a generative AI-based HMI architecture that is effectively deployed across multiple industries remains a major challenge. Variations in data formats, communication protocols, hardware platforms, and user requirements may limit system interoperability and adaptability. Addressing these challenges is vital to achieve widespread adoption of intelligent human–machine collaboration systems in the future.

Conclusion:

Generative AI-assisted Human–Machine Interfaces (HMIs) represent a major advancement in the evolution of adaptive mechatronic decision support systems. As industrial environments become increasingly complex, interconnected, and data-driven, conventional interfaces are no longer sufficient to meet the demands of modern operations. HMIs move beyond simple information display and become intelligent partners that actively assist operators in decision-making, problem-solving, and system optimization. The integration of predictive intelligence enables these systems to analyze large volumes of real-time and historical data, identify emerging patterns, forecast potential failures, and recommend proactive corrective actions. Such capabilities contribute to improved operational reliability, reduced downtime, and enhanced productivity. Immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR) provide intuitive visualization and interaction mechanisms that improve situational awareness and support effective human–machine collaboration. Ergonomic monitoring further strengthens system performance by continuously assessing operator workload, fatigue, posture, and stress levels. It allows the interfaces to adapt dynamically to individual user needs and capabilities. Beyond improving technical efficiency, generative AI-driven HMIs have the potential to create safer, more user-centered, and sustainable working environments. They facilitate better communication between humans and machines, reduce cognitive burden, and support informed decision-making in complex operational scenarios.

References:

[1] M. Grieves and J. Vickers, "Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems," *Transdisciplinary Perspectives on Complex Systems*, Springer, Cham, 2017.

[2] B. Boschert and R. Rosen, "Digital twin—the simulation aspect," *Mechatronic Futures*, Springer, Cham, 2016.

[3] "Transforming Human–Machine Interaction: Generative AI Virtual Assistant," *IEEE Xplore*, 2025.

[4] J. Leng et al., "Digital twin-driven manufacturing cyber-physical system for parallel control and management of smart shop floors," *J. Ambient Intell. Humanized Comput.*, vol. 10, no. 9, pp. 3553–3566, 2019.

[5] Y. Liu et al., "Digital twin-driven human–machine collaboration for smart manufacturing," *IEEE Trans. Ind. Informatics*, vol. 17, no. 6, pp. 4108–4117, 2021.

[6] A. Fuller et al., "Digital twin: Enabling technologies, challenges and open research," *IEEE Access*, vol. 8, pp. 108952–108971, 2020.

[7] S. M. Mousavi et al., "Generative AI in industrial decision support systems: Opportunities and challenges," *IEEE Trans. Syst., Man, Cybern.*, vol. 54, no. 2, pp. 123–135, 2024.

[8] P. Zhang and H. Li, "Adaptive human–machine interfaces using generative AI for robotics," *IEEE Robotics and Automation Letters*, vol. 9, no. 1, pp. 45–52, 2025.

[9] "A Collaborative Human-AI Guided Decision Framework – Gen-Edge-AI," *IEEE Xplore*, 2025.

[10] "Artificial intelligence in modern mechatronic systems: technologies and applications," *Taylor & Francis Online*, 2024.