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Editorial

Advances in Human–Machine Interaction, Artificial Intelligence, and Robotics

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1. Introduction

The convergence of artificial intelligence (AI), robotics, and immersive technologies such as augmented reality (AR), virtual reality (VR), and extended reality (XR) is transforming the way humans interact with machines. Human–machine interaction (HMI) has evolved from simple command-based systems to complex, intelligent interactions that leverage AI to understand and respond to human behavior in real time. As robots become integral to everyday life and industry, there is a growing need to make these interactions more intuitive, efficient, and human-centered.

Recent advances in AI have played a pivotal role in enhancing robotic capabilities, allowing robots to perceive their environment, make decisions, and learn from interactions. Deep learning models, such as convolutional neural networks (CNNs) and large language models (LLMs), have significantly improved robots' abilities in perception, language processing, and decision-making [1]. These models enable robots to recognize objects, understand human speech, and even detect emotions, making HMI more seamless and natural. However, these advancements also bring challenges, such as ensuring the ethical use of AI, managing data privacy, and mitigating biases inherent in AI algorithms [2].

The integration of AR, VR, and XR into robotics further enhances HMI by creating immersive environments where humans and robots can interact in more intuitive and engaging ways. AR technology overlays digital information onto the physical world, enhancing user awareness and control over robotic systems. For instance, AR can be used in industrial settings to provide real-time data visualization, helping operators monitor robot performance or guide robots through complex tasks [3,4]. VR creates fully simulated environments that are invaluable for training and prototyping, allowing users to experiment with robotic behaviors without the constraints of the physical world [5,6]. XR, which encompasses both AR and VR, provides flexible and scalable solutions that blend real and virtual environments, enabling new forms of collaborative robotics [7,8].

This Special Issue brings together cutting-edge research that addresses these multifaceted challenges in HMI, AI, and robotics.

2. The Present Issue

For this Special Issue, 15 submissions were received, and each was carefully evaluated by at least one of the Guest Editors to determine its alignment with the theme of human–machine interaction, artificial intelligence, and robotics. Submissions deemed relevant underwent a thorough review process involving at least two external reviewers, while those that did not meet the criteria were rejected. After a rigorous peer-review process, 11 articles were selected for publication. The accepted contributions explore a diverse array of applications within the fields of human–robot interaction, AI, and robotics, including predictive modeling, immersive technologies, and collaborative decision-making systems. A summary of the findings and conclusions of each article is presented below.

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In the first contribution, Al-Yacoub et al. present a data-driven approach for modeling human–human co-manipulation using force and muscle surface electromyogram (EMG) activities. The study investigates the use of EMG sensors to enhance the mapping between force/torque data and displacements during collaborative manipulation tasks. The authors compare data-driven models, mathematical models, and hybrid approaches, demonstrating that the inclusion of EMG data significantly improves the prediction accuracy of human–robot interaction. Their results highlight the potential of using EMG-enhanced data-driven models to teach robots more intuitive and human-like behaviors in co-manipulation scenarios.

In the second contribution, Martí-Testón et al. propose a novel methodology for producing augmented-reality guided tours in museums using mixed-reality headsets. The study focuses on developing an interactive and immersive visitor experience, specifically designed for the Almoina archeological museum. The authors combine augmented reality with scenographic and theatrical techniques to create a natural and emotive storytelling approach. Their results from usability tests and observational studies demonstrate that this methodology significantly enhances user engagement, making historical content more accessible and personalized. The findings suggest that integrating augmented reality in museum contexts can revolutionize how heritage is experienced, offering a more intuitive and emotional connection to the past.

In the third contribution, Kim et al. explore the dynamics of human and AI speaker interaction, focusing on communication failures categorized into system, semantic, and effectiveness errors. Using data from major AI speaker users in South Korea, the study investigates how different types of communication failures impact user satisfaction and continued use of the AI speakers. The findings reveal that system and semantic errors negatively affect sustained usage, while effectiveness failures, surprisingly, do not deter users, especially among single-person households, such as elderly users. The study concludes that AI speakers can significantly alleviate loneliness in these demographics and highlights the importance of designing AI systems that effectively manage communication failures to maintain user engagement.

In the fourth contribution, Castillo-Vergara et al. explore the acceptance of Industry 4.0 technologies among technical students from rural areas, using an extended Technology Acceptance Model (TAM). The study aims to understand how factors like technological optimism, subjective norms, and facilitating conditions influence students' perceived usefulness, ease of use, and intention to adopt these technologies. The results indicate that technological optimism positively impacts perceived usefulness and ease of use, though it does not directly affect the attitude towards using the technology. Facilitating conditions and subjective norms also play crucial roles in shaping students' intentions to use Industry 4.0 technologies, suggesting that a supportive environment and positive social influences are critical for successful adoption. The findings provide valuable insights for policymakers and educators aiming to enhance technology integration in educational settings.

In the fifth contribution, Xie and Shen develop a lightweight KD-EG-RepVGG network for detecting surface defects in strip steel using structural reparameterization, efficient channel attention (ECA), and Gaussian error linear units (GELU). The study aims to enhance the speed, accuracy, and stability of defect identification in industrial applications. The proposed model demonstrates a high defect recognition accuracy of 99.44% and a rapid detection speed of 2.4 ms per image. Compared to traditional and other deep learning models, the KD-EG-RepVGG network achieves superior performance while maintaining a low computational cost, making it highly suitable for deployment in real engineering environments.

In the sixth contribution, Castiblanco Jimenez et al. compare user engagement (UE) between advergames and traditional advertising using electroencephalography (EEG) to assess its influence on purchase intention. The study explores how interactive advertising formats like advergames can enhance user engagement compared to passive formats such as TV commercials. The findings reveal that advergames significantly increase engagement levels, as measured by EEG, compared to traditional advertisements. Furthermore, the study concludes that higher engagement levels positively influence the user's purchase intention, suggesting that more interactive and engaging advertising strategies can be more effective in driving consumer behavior.

In the seventh contribution, Mandischer et al. propose an adaptive human–robot collaboration system aimed at including people with disabilities (PwD) in manual labor tasks. The study introduces a novel approach that uses a two-stage reasoning system combined with a matchmaking ontology to align the capabilities of PwD with specific task requirements. The methodology involves real-time assessment of individual capabilities using sensor data, which then guides task allocation between the human and the robot. The results highlight that this system allows robots to autonomously adapt to the user's in situ capabilities, significantly enhancing the inclusion of PwD in the workforce by making collaborative workplaces more flexible, accessible, and economically viable.

In the eighth contribution, Mourtzis et al. propose a novel approach for optimizing the reliability of robotic cells using digital twin (DT) technology and predictive maintenance (PdM). The study focuses on improving the reliability of critical components within robotic cells by leveraging real-time data monitoring and machine learning algorithms to predict failures before they occur. The authors developed a DT model that integrates with a predictive maintenance framework, allowing for continuous monitoring and assessment of component health. Results demonstrated that implementing this approach significantly reduces unexpected downtimes and maintenance costs, thereby enhancing overall system reliability and performance in manufacturing environments.

In the ninth contribution, Burčiar et al. present a methodical approach to enhancing proactivity in production processes using a digital twin (DT) integrated with a simulation-based decision-making framework. The study focuses on integrating a DT with a Manufacturing Execution System (MES) to enable real-time analysis and proactive order management. The proposed Manual Order Rearrangement (MOR) method demonstrates the ability to simulate and optimize production scenarios before execution, significantly reducing downtime and resource waste. Experimental results show that the implementation of DT technology improves process efficiency by optimizing production schedules and minimizing potential errors, highlighting the potential of DTs in advancing smart manufacturing practices.

In the tenth contribution, Lee et al. introduce a mission-conditioned path planning approach using a Transformer Variational Autoencoder (CVAE) to integrate mission specifications through Linear Temporal Logic (LTL) into robotic path planning. The proposed framework combines the CVAE with a Transformer network to generate control sequences that meet LTL specifications while optimizing trajectory costs. The study demonstrates that the approach outperforms traditional sampling-based and deep-learning methods in terms of computational efficiency, trajectory quality, and mission success rates. The results highlight the framework's capability to handle complex mission requirements, ensuring adherence to predefined specifications while navigating challenging environments effectively.

In the final contribution, Torrejón et al. present the design and development of Shadow, a cost-effective mobile social robot intended for human-following applications. The study emphasizes the use of 3D printing technology for rapid prototyping and customization, allowing for a highly agile and adaptable robot. Key features include omnidirectional movement, advanced sensors such as 360° cameras and 3D LiDAR, and a flexible power electronics system. Extensive testing demonstrated Shadow's stability, agility, and ability to operate autonomously for at least seven hours, successfully advancing from technology readiness level (TRL) 2 to TRL 7 within a year. The results highlight Shadow's potential as a versatile, low-cost solution for various human–robot interaction scenarios.

3. Further Directions

As the fields of HMI, AI, and robotics continue to evolve, several key areas warrant further exploration. First, the development of more sophisticated AI models that can understand and predict human intentions will be crucial for advancing HMI. Future research should focus on creating transparent AI systems that provide justifiable decisions, particularly in applications where safety and ethical considerations are paramount.

Significant challenges remain in making XR technologies accessible and user-friendly. One critical issue is designing interaction models that reduce cognitive load, making it easier for users to control and collaborate with robots. In medical robotics, for example, surgeons use VR-based training systems to practice complex procedures, reducing the risk of errors in actual operations. Such applications demonstrate the potential of immersive technologies to improve skills and safety, yet also highlight the need for continuous refinement to ensure that these systems are both effective and intuitive.

Ethical considerations are also at the forefront of HMI research. As robots and AI systems become more autonomous, questions arise about accountability, transparency, and user trust. There is an urgent need for frameworks that ensure AI-driven decisions are interpretable and align with human values, particularly in high-stakes areas like healthcare and autonomous driving. Public acceptance of robots will depend not only on technological advancements but also on the perceived fairness, safety, and reliability of these systems.

Additionally, the role of AR, VR, and XR in enhancing HMI will expand, with future work needed to improve the usability and integration of these technologies in everyday robotic applications. This includes optimizing interfaces to reduce cognitive load and developing standards for safe and ethical interactions in virtual environments. There is also significant potential in leveraging these technologies for education and training, particularly in fields like healthcare, where realistic simulations can greatly enhance learning outcomes.

Finally, as robots become more autonomous, it will be essential to develop regulatory frameworks that address the ethical implications of HMI. This includes ensuring that AI systems are free from biases, respect user privacy, and operate transparently. Collaborative efforts between technologists, ethicists, and policymakers will be necessary to guide the responsible development of these technologies and ensure they are deployed in ways that benefit society.

By addressing these future directions, the research community can continue to push the boundaries of what is possible in HMI, AI, and robotics, paving the way for a future where intelligent machines work seamlessly and safely alongside humans.

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