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Review

Emerging Technologies in Human-Machine Interaction towards Industry 5.0 and Industrial Metaverse: Challenges and Opportunities

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Abstract: Since the first steps towards manufacturing system digitalization, the development of interfaces enabling interaction between humans and machines has progressed in parallel. With the appearance of novel technologies such as 3D-modeling or Artificial Intelligence, Human-Machine Interfaces are required to provide access to larger amounts and complexity of information, as well as more complex control capabilities. There are currently many different approaches to Human-machine Interaction, such as User Interfaces and Extended Reality. This research work summarizes the history of Human-Machine Interfaces, provides a timeline of their evolution based on the Industrial Revolutions, and showcases recent advancements and emerging technologies in the field. A review methodology considering the newest and most impactful works in the field is followed, and challenges and opportunities towards Industry 5.0 and the Industrial Metaverse are identified and discussed.

Keywords: Human-Machine Interaction; human-machine interface; industry 5.0; industrial metaverse

1. Introduction

1.1. Challenges

Through the Industrial Revolutions, humanity has leveraged technological advancement towards the improvement of products, systems, and quality of life. What started with steam and coal power, as well as manually operated machine tools, has now reached an automated stage where Digital Twins (DTs), the Internet of Things (IoT), Artificial Intelligence (AI), and Cloud Computing, among other Key Enabling Technologies (KETs), bridge the gap between the physical and digital world. The current iteration of Industrial Revolution, also known as Industry 4.0, utilizes these technologies together to create Cyber-Physical Systems (CPSs) [1]. These mostly automated systems perform data processing and analytics swiftly on a digital level to provide insight into the physical system operations, improving processes and enhancing efficiency [2]. However, significant challenges have surfaced in the paradigm of Industry 4.0, which were highlighted during the COVID-19 pandemic, including the lack of resilience and flexibility of production systems and the importance of human oversight [3]. These challenges were not initially apparent in Industry 4.0, as industrial flexibility was considered a priority for CPSs. The increasing impact of globalization has shown that hyper-focusing on shop-floor flexibility is not the optimal approach however, as dynamic market conditions can overpower isolated system adaptability [1]. Instead, the proposed industrial paradigm of Industry 5.0 places industrial and environmental sustainability at its core, in combination with system resilience through the entire supply chain and an enhanced focus on the human aspect of manufacturing systems, both for working conditions and utilization of uniquely human capabilities [1,4].

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Based on the pillars of human-centricity, sustainability, and resilience, the goal of Industry 5.0 is to facilitate not only industrial but also societal evolution [5,6]. This evolution is met with its own set of challenges, as its three core pillars can act both in a complementary as well as a contradictory manner [7]. Utilizing the human factor in manufacturing can improve the decision-making process, but at the same time reduces operational consistency over longer periods of time. Advanced technology implementation is another example of this, as AI and DTs facilitate system resilience, but their integration creates additional stress on time utilization, supply chain logistics, and environmental resources. To address these challenges, systematic integration of advanced KETs under a single, holistic framework is required [4]. Metaverse, and its subset for manufacturing systems dubbed the Industrial Metaverse, describes the goal of technological integration towards seamless physical and digital interconnectivity, utilizing all available resources in such a way that the challenges presented by one are overcome by the function of another. Industrial Metaverse sounds like the ideal solution to address the challenges of Industry 5.0, however its realization is still in its infancy due to technological constraints, ethical and regulatory concerns, and significant lack of trust [8].

As such, there has been limited research concerning Industrial Metaverse as a holistic framework in recent years. In particular, the rapid advancement of AI-related technologies has received most of the hype and the scientific spotlight [9]. However, as described in [10], AI is one of the major enabling technologies of Industrial Metaverse, which means its rapid advancement is a major driver towards wider adoption. Additionally, despite this apparent delay in the advent of Industrial Metaverse, companies such as Siemens and Hyundai have invested deeply in manufacturing facilities operating based on its framework [11,12].

1.2. Problem Definition

Several approaches of Industrial Metaverse definition have been made, but their common characteristics describe a virtual environment symbiotic to real environments in real-time, both in form and in function. Industrial Metaverse utilizes all the Key Enabling Technologies (KETs) of Industry 4.0 and 5.0 and employs the usage of advanced cutting-edge technologies, such as Blockchain and Edge Computing, to integrate the physical and digital worlds, enabling remote cooperation and enhanced operations [4]. A significant portion of its focus is given to Human-Machine Interaction (HMI) technologies, mostly Extended Reality (XR), as they enable human immersion in digital worlds and facilitate interoperability between physical and digital systems [8]. However, XR is far from the only interface enabling communication between humans and machines. In recent years, several technologies have emerged or improved to support efficient and effective HMI, and each of these technologies presents its own challenges and opportunities for the transition towards Industry 5.0 and Industrial Metaverse.

1.3. Research Contribution

The purpose of this research is the discovery of HMI technologies relevant to the advent of Industry 5.0 and Industrial Metaverse. An overall review of such technologies in manufacturing is conducted, and the most prominent technologies and methods are identified. For each of these technologies, a systematic literature search is conducted, recent advancements are highlighted and important challenges and opportunities are presented. Additionally, cutting-edge biotechnologies for HMI are addressed and discussed.

1.4. Structure of Research Work

The rest of the paper is structured as follows. Section 2 provides a brief overview of the history of HMI and the Industrial Revolutions, up to Industry 4.0. The Literature Review methodology is described in Section 3, and the resulting State of the Art and emerging technologies are presented in Section 4. Challenges and opportunities of these emerging technologies towards Industry 5.0 and Industrial Metaverse are discussed in Section 5. Finally, Section 6 concludes the paper and provides outlook.

2. History of Human-Machine Interaction

Four major Industrial Revolutions (Industry 1.0 to Industry 4.0) have taken place since the second half of the eighteenth century, and the world is currently progressing toward Industry 5.0. Industry 1.0 revolutionized manufacturing systems with new mechanical production facilities using steam and coal power. Industry 2.0 started in the 1870s due to the electrification of systems and Taylor's work division with mass production. Industry 3.0 is associated with the introduction of digital platforms and took place in the 1970s. Industry 4.0 began in the early 2000s, during which technological integration and digitalization are the main architectural concepts [13].

With every new iteration of Industrial Revolution, the model of Human-Machine Interaction (HMI) transitioned accordingly, as depicted in Figure 1. During Industry 1.0 and Industry 2.0, before the two World Wars, machines were considered tools for humans to set up, operate, or fix. HMI in this era was limited to factory layout, manual control, and machine maintenance [13]. The role of humans in manufacturing systems was still mostly similar to that of a machine, performing a specific task repeatedly with minimal variation or decision-making required, and being evaluated using similar factors such as production rate [14]. Automation capabilities surfacing during Industry 3.0 began the first real transition of HMI, shifting the role of humans in manufacturing from operators to overseers. Many manual tasks that used to be performed by humans were automated, allowing humans to focus on using their creativity and cognition. Additionally, since the rate of technological advancement made worker training and reskilling challenging or even impossible, the design of machines that still required human operators started focusing on simplicity and natural operational understanding to reduce training times [13].

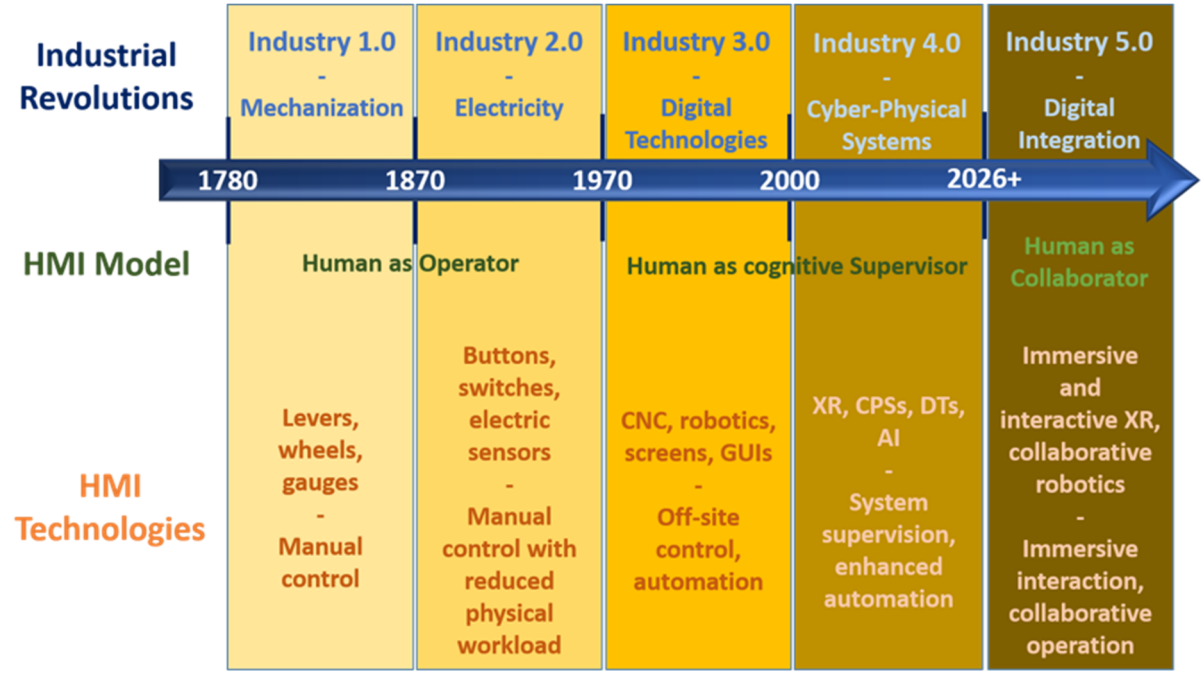


Figure 1. Timeline of Industrial Revolutions and Human-Machine Interaction.

HMI is one of the major drivers of digital transformation introduced in Industry 4.0. During this era, it is described as a critical enabler which ensures transparency, safety, and usability in highly automated systems. Advanced interfaces such as visualization dashboards, Augmented Reality (AR), and decision-support tools are designed to assist humans in understanding machine behavior. Industry 4.0 primarily engages humans in roles regarding cognitive and supervisory tasks, indicating the importance of trust and situational awareness when collaborating with machines [13].

The transition towards Industry 5.0 is still ongoing, however, HMI model is expected to follow this transition. The pillars of human-centricity, sustainability, and resilience shift the role of humans in manufacturing systems once more, from supervisor to colleague, which brings about a new set of challenges and opportunities for HMI to be identified and considered [14].

The HMI model prevalent in every Industrial Revolution is directly affected by the available technologies of the time. In Industry 1.0, HMI is limited to manual control of machines because interfaces are limited to levers, wheels and other means of manual handling. Similarly, sensors comprise direct measurement and analogue visualization using needles and gauges, often integrated directly into the machines. With the advent of electricity and Industry 2.0, levers and wheels that require physical strength are replaced by buttons and switches, which reduce manual effort. However, these interfaces still require manual control from the user. Similarly, while novel types of sensors appeared, measurements still rely on physical system integration. It was not until the integration of the first digital technologies in manufacturing that humans transcended their roles as operators to become overseers and supervisors. This paradigm shift was driven by technologies such as Computer Numerical Control (CNC) and screens with Graphical User Interfaces (GUIs), which allowed programming and automation of machine operations from off-site. Robotic systems also made an appearance around this time, together with the first XR equipment and platforms. Although these systems drastically altered the industrial landscape, their full

potential could not be realized due to the lack of horizontal and vertical integration in manufacturing systems. Utilizing Industry 4.0 technologies, such as CPSs, AI, and DTs, the data obtained from each automated manufacturing cell is synthesized to provide a holistic overview of the system. This allows supervising engineers to oversee the whole of the manufacturing system. Additionally, while XR technologies had already been developed, this era saw an increased interest in the Research and Development (R&D) of monitoring systems utilizing their capabilities, which led to interfaces such as the Head-Mounted Display (HMD), providing individual access to immersive visualization [15,16].

Industry 5.0 is the first iteration where the HMI model is not driven by the available technologies, but rather the other way around. As mentioned earlier in this section, Industry 5.0 focused on the pillars of human-centricity, sustainability, and resilience. As such, instead of directing the HMI model towards overall improvement of productivity and efficiency, which was the case for Industry 4.0, the goal is to create a sustainable industrial environment, both for workers and for the market. The need to combine human versatility and expertise with machine power, speed, and precision led to a shift in technological advancement focus. XR platforms are not used solely for system monitoring or prototyping and simulation anymore, but rather as interactive environments which provide adaptive control capabilities, enhanced human-to-machine communication, and immersive visualization, reducing manual effort and cognitive workload. Similarly, traditional robotic systems are replaced with collaborative robots, sacrificing a part of their production efficiency to utilize human flexibility and support a production model based on the customization and personalization of products and consumer experience [2].

3. Literature Review Methodology

The methodology followed for the literature review is described in Figure 2. The Scopus scientific database was chosen for this research work, as it contains literature from multiple, diverse sources, its entries all belong to verified, cross-referenced databases, and the Impact Factor of the publications containing these papers is usually significant. All searches were conducted with a timeframe between 2021 and 2026. The lower limit was derived from the emergence of Industry 5.0 as a popular term, whereas the upper limit was added for replicability and posterity.

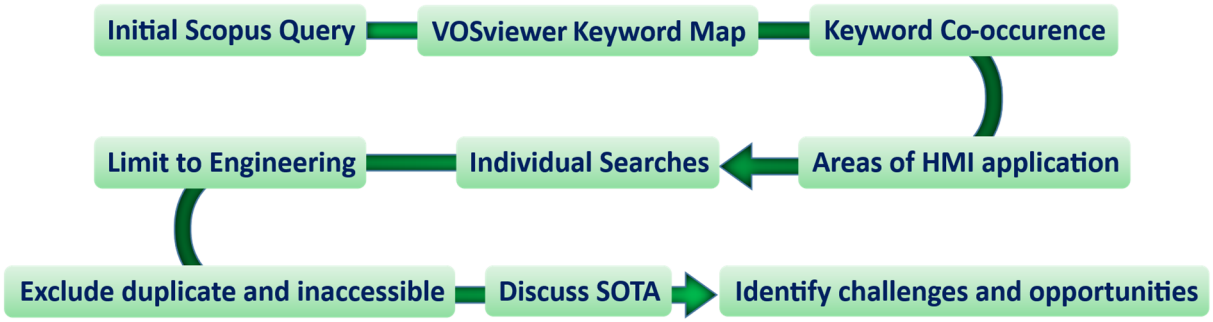


Figure 2. Literature review Methodology.

The initial search query was targeted at the identification of cases and applications of Human-Machine Interaction in manufacturing. The exact query was: [TITLE-ABS-KEY (“human machine interaction*” AND manufacturing) AND PUBYEAR > 2020 AND PUBYEAR < 2027]. The results of this search were processed and analyzed using the VOSviewer 1.6.18 software which specializes in keyword association. Specifically, the author and index keywords of about 530 publications were categorized to determine the most common ones. By limiting the number of occurrences to 15 and above, a total of 53 keywords were extracted. Using these, a keyword network map was constructed through the software, shown in Figure 3, which maps the keywords by family and strength based on their co-occurrence. Out of these, some were obvious, such as “human-machine interaction”, or did not refer to HMI technologies but rather their context, such as “manufacturing process”.

Due to the complexity of the map created by the software, the Scopus database keyword metadata was used to create an abstracted version, presented in Figure 4, which clearly shows four areas of keyword co-occurrence:

- Collaborative technologies
- Sensors
- Augmented and Virtual Reality (AR and VR)
- Robotics

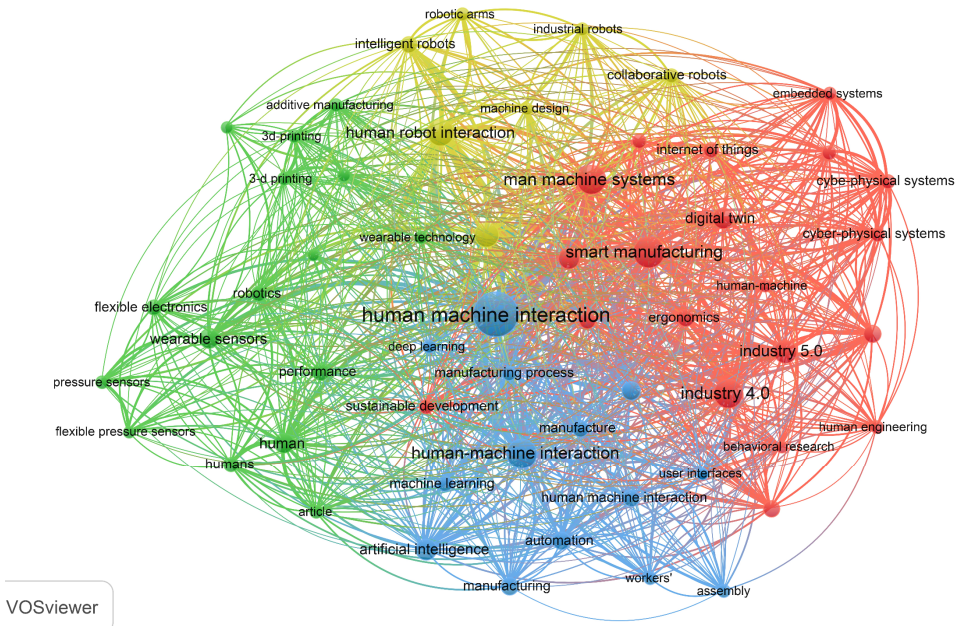


Figure 3. HMI keyword network map.

These areas are not distinct or mutually exclusive but rather interconnected on several levels. Collaborative technologies form the highest and most general level, which describes the context of HMI applications, including Industry 4.0, Industry 5.0, and smart manufacturing, as well as DTs, CPSs, IoT, and more. This context is of primary concern in most applications and appears throughout the other three levels. The second level is defined by sensors and sensing technologies, which form the backbone of HMI by digitizing information from the physical world to be used in digital applications and data analytics. The third level contains AR and VR applications, which are described together with Mixed Reality (MR) under the umbrella term Extended Reality (XR). These technologies support most advanced interfaces in preparation for the transition towards Industrial Metaverse, gradually replacing computer and touch screens, which did not appear in the prevalent keywords. Finally, robotics appear to be the main area where HMI applications are focused, utilizing novel sensing technologies and dynamic XR interfaces to enable human-robot collaboration in industrial manufacturing environments.

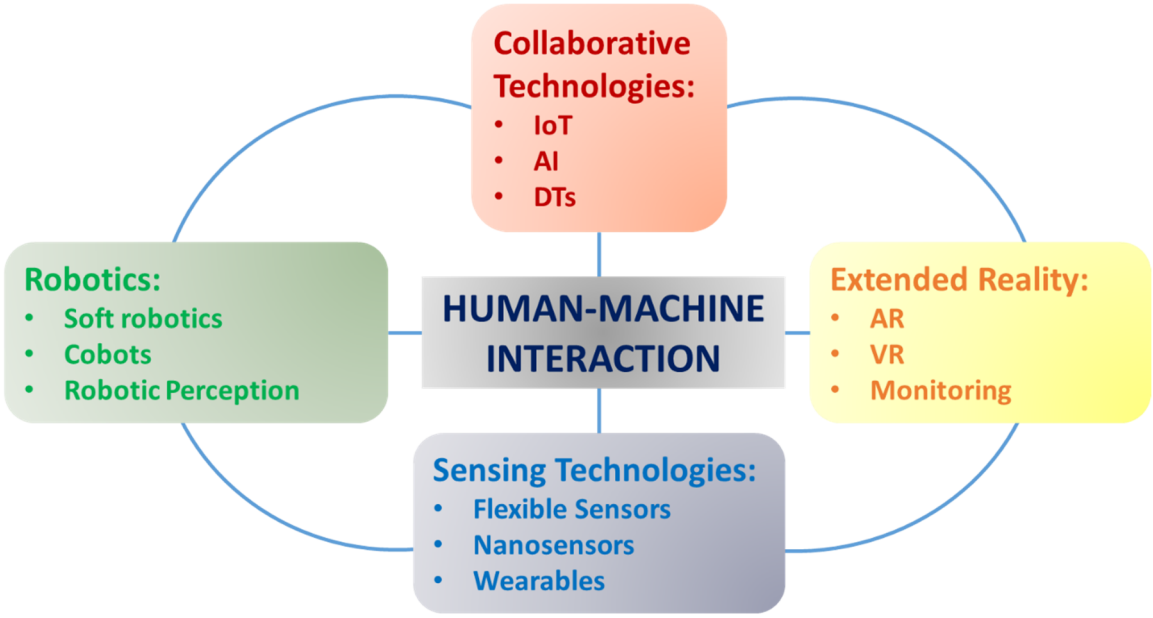


Figure 4. Categories of modern HMI applications.

Further searches were conducted on Scopus and Google Scholar based on these categories. Specifically, the three additional queries were:

1. TITLE-ABS-KEY ("human machine interaction*" AND manufacturing) AND TITLE (robot OR cobot OR robotic) AND PUBYEAR > 2020 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA, "ENGI"))
2. TITLE-ABS-KEY ("human machine interaction*" AND manufacturing) AND TITLE ("augmented reality*" OR AR OR "virtual reality*" OR VR) AND PUBYEAR > 2020 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA, "ENGI"))
3. TITLE-ABS-KEY ("human machine interaction*" AND manufacturing) AND TITLE (sensor OR device) AND PUBYEAR > 2020 AND PUBYEAR < 2027 AND (LIMIT-TO (SUBJAREA, "ENGI"))

In these queries, the subject area was limited to engineering to ensure relevance to the context of Industry 5.0 and Industrial Metaverse. Finally, after duplicates and inaccessible publications were excluded, all remaining material was utilized. The State of the Art and emerging technologies presented in Section 4 is the product of 87 distinct publications, several of which cover the convergence of multiple levels. A summary of the results can be found in Table 1.

Table 1. Summary of literature search results.

Technology	Category	Number of Papers	Percentage of Total Papers in Category
Sensors (40 papers)	Humidity Sensors	2	5.0%
	Flexible Sensors	27	67.5%
	Tactile Sensors	3	7.5%
	Hybrid Sensors	3	7.5%
	Other Sensors	5	12.5%
	Environmental Monitoring	9	22.5%
	Health Monitoring	15	37.5%
	Wearables	12	30.0%
	Materials	14	35.0%
	AI	6	15.0%
	Robotics	5	12.5%
Robotics (26 papers)	Robotic Perception	5	19.2%
	Cobots	7	26.9%
	Soft Robotics	4	15.4%
	Social Robots	3	11.5%
	Learning Robots	2	7.7%
	Sensors	2	7.7%
	DTs	4	15.4%
	Manufacturing	4	15.4%
	Health	4	15.4%
	AR	1	3.8%
XR (21 papers)	AR	17	81.0%
	VR	6	28.6%
	Manufacturing	4	19.0%
	AI	3	14.3%
	DTs	3	14.3%
	Devices	3	14.3%

Similar Research

Scientific review publications considering HMI have been made in the past. However, these attempts focused either on the human side of HMI [13], on the general model of HMI in Industry [15], and on specific HMI technologies [17]. To the best of our knowledge, an overall review of HMI technologies and applications has not been conducted yet.

4. State of the Art and Emerging Technologies

4.1. Sensing Technologies

Sensing technologies facilitate the digitization of things in the physical space, ensuring high fidelity and immersion in the digital space. Due to the evolution of manufacturing equipment, as well as the integration of humans in the manufacturing processes, Flexible Sensors have been identified as the most researched sensor type. These sensors maintain their sensing abilities in dynamic environments and are ideal for human or machine integration. Most of these are Flexible Pressure Sensors [18–40]. However, several other types exist, including

Tangential Flexible Sensors [41], Flexible Vibration Sensors [42], Flexible Bending Sensors [43,44], and Flexible Thermal Sensors [45]. Each of these sensors fulfills a different role, however, their characteristic flexibility makes them ideal for wearable applications [20,22,27,29–31,35,38,46,47], including health monitoring and rehabilitation [21–23,27,30,32,35,38,39,47–49], as well as electronic skin [23,25,27,39]. In a manufacturing context, Flexible Sensors are also used in robotic systems, primarily in soft robotics and robotic grippers handling sensitive or fragile materials and objects [18,19,44]. Flexible Pressure Sensors have also been used for health monitoring in conjunction with Virtual Reality (VR) technologies [40].

Other types of modern sensors include tactile sensors, which also enable robotic object recognition and facilitate soft robotic applications [50–52], humidity sensors, which facilitate environmental monitoring for factories, agriculture, and smart homes [53,54], electromyography sensors used for human motion detection [48], proximity sensors used for human motion detection specifically in robotic manufacturing environments [55], and acceleration sensors which fulfill a variety of applications, including some in hazardous environments such as underwater [49]. Most of these sensors are wireless, allowing freedom of movement and reducing cable management requirements and hazards [56]. Some of these sensors are inspired by the form and function of natural organisms, a concept known as biomimicry. These are usually Flexible Sensors and are used mostly in applications of soft robotics [31,34,57,58]. Additionally, many of these sensors are also used to collect data which is then forwarded to Machine Learning (ML) and Deep Learning Artificial Intelligence (AI) algorithms [36,41,50,51,59,60], often in collaboration with Augmented Reality technologies in some applications [61–63]. Finally, Hybrid Sensors combining the functionality and purpose of two or more of the other sensor types are also being developed [59,64,65].

4.2. Extended Reality

While Extended Reality (XR) technologies are not the only technological advancements facilitating Human-Machine Interaction (HMI), they are the primary focus the concerning interface between humans and machines. Some of these applications focus on Virtual Reality (VR) [40,66–69], facilitating system sustainability [66] through advanced simulation techniques [67,68], as well as health monitoring and rehabilitation [40,68]. Most XR research, however, promotes Augmented Reality (AR) approaches [61–63,66,70–82], including system visualization and worker training for Additive Manufacturing [63,70], evolution and novel applications of Heads-Up Displays (HUDs) [77,78], and especially operator assistance, which finds extensive utilization in diverse manufacturing environments [73,75–77,80,82]. Apart from manufacturing applications, AR interfaces are also utilized in education and social settings [82].

4.3. Robotics

General research concerning the interaction between humans and robots in manufacturing is still ongoing [83–87], with special focus on robotics operator assistance utilizing Augmented Reality (AR) technologies [82]. Another major field supporting the potential of Human-Machine Interaction (HMI) with robotic systems is Digital Twins (DTs) [88–91], which support real-time visualization and decision making through AR and Virtual Reality (VR) interfaces [69,72,79]. In the context of HMI, Collaborative Robots (Cobots) also play a major role, utilizing human flexibility and robotic precision to support production efficiency and safety [92–98].

Novel research and applications of robotic HMI explore robotic perception, soft robotics, and humanoid robots. Robotic perception refers to the ability of robots to process data from integrated sensors regarding their environment, usually in the form of Flexible Pressure Sensors used to support precision gripping and handling of sensitive objects or proximity and wearable sensors translating human motion into obstacle awareness for the robotic system [18,26,84,98–100]. Soft robotics encompasses robotic systems made of soft, flexible materials, which enable specialized applications [101]. These systems utilize Flexible or Tactile Sensors as the most suitable for system integration [19,44,51], and their shape or function are often inspired by biomimicry [57,58]. Finally, humanoid robots are being considered as candidates for future Cobots, inheriting a greater portion of human flexibility and facilitating a more natural approach to collaboration and service provision, including both manufacturing and health monitoring applications [102,103].

4.4. State of the Market

When considering HMI applications in Industry, it is important to highlight the technologies readily available in the market, as well as those utilized in industrial R&D and operations. The global market for HMI technologies and platforms in industry showcases the current development stage and potential solutions to future challenges, as well as the incentive and opportunity available for industrial researchers. The market size was estimated at 5.63 billion USD in 2024. Projections estimate that this value will increase up to 10.57 billion USD in 2032, with

projections calculating the Compound Annual Growth Rate (CAGR) at 8.2% between 2026 and 2032. This projection accounts for different types of interfaces such as panels, desktops, and portable devices, as well as different displays, including monochrome, color, touchscreens, Augmented Reality glasses, and Virtual Reality lenses. Modern interfaces come equipped with various functionalities, such as touch, gesture, and voice control [104]. A network of processors, switches, hubs, routers, and gateways supports HMI by providing the infrastructure necessary for high-speed, high-fidelity communication [105].

The HMD devices available to the public also evolve at a rapid rate, with the latest top iterations being META QUEST 3 and 3S for VR and Viture Beast for AR. META QUEST 3S runs on a Qualcomm Snapdragon XR2 Gen 2 chipset, with 1832 × 1920 resolution per eye, 8 GB of RAM, and weighing about 0.5 kg. Despite showing great performance capabilities, it is also considered one of the most compact and affordable devices of this type. However, its adoption is limited due to ergonomic reasons common to VR headsets, as well as its short battery life. Alternatively, the Viture Beast glasses are utilized with external devices, carrying no integrated chipset or RAM, and their resolution is lower at 1920 × 1200 pixels; however, they only weigh 0.05 kg and offer a smart, subtle, and ergonomic design. While they are considered by some as the best glasses for AR in 2026, they still suffer from chromatic aberrations and sub-optimal color fidelity [106].

At the enterprise level, companies such as Unity and Epic Games provide graphics engines (Unity Engine and Unreal Engine) to design AR and VR applications, while Meta, NVIDIA, AMD, and more provide the necessary hardware and compatible software development kits, supporting R&D in all fields, including industrial operations [107]. Finally, enterprises have also developed novel HMI applications in recent years. For example, the ACG Group in India developed AI models for initial configuration of machines during setup, which operators can then train further and refine based on their performance. Kunlene Film Industries in China have integrated an Industrial Internet of Things (IIoT) platform with AI and a human-in-the-loop architecture, allowing operators to review the adjustments proposed by the intelligence engine in real-time. Finally, Schneider Electric in China has introduced a set of AR glasses with integrated Generative AI capabilities, which can identify and display the potential causes of manufacturing problems and provide solutions, drastically reducing the mental workload of operators and the rate at which they master the machines they operate [108].

5. Discussion: Challenges and Opportunities

Through the literature reviewed in Section 4, several challenges and opportunities for each level of Human-Machine Interaction (HMI) have been identified, which are included in Appendix A, summarized in Table 2, and discussed in this Section, along with a critical assessment of the Technology Readiness Level (TRL) of the product or application presented in each referenced work. Specifically, the TRL framework utilized is the one employed by the European Commission for Horizon 2020. The framework is structured as follows [109]:

- TRL 1: Observation of basic principles. Only the fundamental scientific blocks are described.
- TRL 2: Technological concept. Function and purpose are fully described.
- TRL 3: Proof-of-Concept. The central function has been experimentally tested successfully.
- TRL 4: Laboratory validation: All functions have been experimentally tested in a fully controlled environment.
- TRL 5: Relevant environment validation. All functions have been experimentally tested in a real operational environment, under controlled conditions.
- TRL 6: Relevant environment demonstration. All functions have been applied in a real operational environment.
- TRL 7: Prototype demonstration. System has operated successfully in a real industrial environment.
- TRL 8: System completion and qualification. System is complete and has been qualified through relevant standards and regulations.
- TRL 9: Proven system. System is complete and operates normally in competitive industrial environment.

5.1. Sensing Technologies

Following the digitalization of manufacturing systems at a global scale [76], demand for sensing technologies facilitating this process has also increased. As such, sensor manufacturing scalability has emerged as a major challenge in recent years [24,46,51,53]. Due to the increasing focus on human-centricity, sensors are required to possess significant stretchability and durability, allowing them to be integrated into mobile machines, wearable devices, and clothing and thus supporting active participation of humans in the manufacturing process [20,24,25,27,35,38,42,49,65]. Simultaneously, system and process resilience, as a pillar of Industry 5.0, necessitates precision and accuracy for sensing technology performance in order to minimize uncertainties [22,31,47,50,54], with

improved robustness in case of interference [20,27,32,34,36,43,48,65] and range-sensitivity-stretchability ratios, which translate to overall improved performance [21,26,28,30,32,36,38,45,46,49]. Finally, sustainability requirements dictate the need to reduce the financial cost and the energy consumed for sensor development and application [21,31,32,34,49,56,64], which can also be achieved through the usage of multidirectional or multifunctional sensors, which would result in a reduced total number of sensors used [22,25,36,41,44,64]. The combination of these factors requires the development of sensors which traditional materials and manufacturing processes are incapable of producing. However, advanced materials and processes, including additive processes, exist or are being actively developed and have proven capable of meeting several of these requirements [23,29,32,33,35,45,46,54,55,64,65]. Challenges still arise during the selection of compatible materials and suitable processes [23,28,29,36,37,45,47], as well as in the design of the microstructure, which plays a major role in sensor functionality and performance [23,36,39,47,52]. Sensors that conform to the requirements of Industry 5.0 allow for seamless integration of Artificial Intelligence (AI) and Internet of Things (IoT) with both humans and machines, usually robots [27,36,39,41,44,50,51,55,59], facilitating the transition toward the framework of Industrial Metaverse [10].

Recent developments in sensing technology are largely focused on human integration. Electromyography and electroencephalography are two important sensor types which, in combination with advanced ML techniques, can be utilized to predict human motion and action and provide actionable insights for collaboration to interactive machines and robots [110]. A significant limitation of sensing technology advancement is highlighted in Table 2, where the TRL of developed sensors is limited to between 3 and 4, with only a single case among forty showing TRL 5. This limitation is caused by a significant disciplinary gap, since sensor developers are often material and microstructure experts rather than manufacturing system specialists. As such, a multidisciplinary approach is suggested to sensor integration and development to bridge the gap between their production and utilization and facilitate extensive testing in real industrial environments. A single case successfully integrating sensors to operational robotic systems was discovered [18], showcasing the necessity to bridge this gap.

5.2. Extended Reality

As described in Section 2, the role of humans in manufacturing systems is shifting from supervisory and decision-based to collaborative. Thus, comfortable, intuitive, and informative interfaces are required [61,62,66–68,74,78]. In the context of digital integration facilitating Industry 5.0 and Industrial Metaverse, Extended Reality (XR) and specifically Augmented and Virtual Reality (AR & VR) have proven the most prolific interfaces of the future. AR and VR technologies provide several opportunities to address the emergence of challenges such as manufacturing downtime [70], sustainability [66,70,75], resilience [76], and adoption of prescriptive maintenance toward quality improvement [68,75], as well as process design, optimization, and control [63,68,72,73,77,79,81]. Immersion and visualization are primary opportunities concerning these challenges [63,67,70,72,73,76–78,80,81], supporting efficiency, productivity, flexibility, and quality improvement [61,77,80,81]. Another major opportunity provided by these interactive technologies against the emerging challenges is worker training and decision-making support [63,70,75–77]. Utilizing the potential of these opportunities is only made possible through the integration of humans, sensors, robots, Artificial Intelligence (AI), Digital Twins (DTs), and the Internet of Things (IoT) throughout the supply chain [62,63,68,69,71,74,87], as described under the framework of Industrial Metaverse [10]. The real-time visualization capabilities necessary for effective Human-Machine Interaction (HMI) require significant computing power, both in terms of hardware and in terms of software, which have limited the integration of AR and VR technologies in manufacturing systems [81]. However, rapid technological advancement of devices and infrastructure promise to open the path in the near future [66,80]. Additionally, novel frameworks for combining XR technologies with DTs are being developed, resulting in more streamlined models which require less computing power, thus facilitating this transition even further [111].

While AR and VR technologies have been around for more than two decades, their full potential is only now beginning to be realized. During the era of Industry 4.0, XR was used mostly for simulation and prototyping, reducing development cost and time-to-market. In the context of Industry 5.0, the focus is shifted toward using XR for operator training and support, processes which also assist in efficiency improvement while simultaneously benefiting the sustainability of the working environment and the mental well-being of human workers. Based on the Industrial Metaverse framework, XR technologies also provide opportunities for remote collaboration of both humans and machines through co-existence in a unified digital environment. Operator training potential can also be significantly improved by combining the immersive training environment with the remote supervision of a senior engineer and the development of varied educational scenarios and tasks using Generative AI techniques [81,104,108].

5.3. Robotics

As a result of the global transformation of manufacturing systems [88], market demand force industries to reduce manufacturing times and increase throughput [18]. Simultaneously, the dynamic state of the global market [84,95] forces systems to be flexible, and disruptive conditions such as the COVID-19 pandemic highlighted the necessity of robustness, which combines with flexibility to form the pillar of resilience as per the paradigm of Industry 5.0 [103]. Additionally, the increasing focus on human presence and Human-Machine Interaction (HMI) in manufacturing systems [83,84] has raised sustainability concerns, oriented not necessarily toward the environment but rather mostly toward human agency, safety, and job security [92,93,96,102,112]. The result of these challenges is a shift toward large-scale integration of robotics in manufacturing systems. Robotic systems can perform traditional processes while adding a layer of multifunctionality, flexibility, and integration capabilities [57,84,85,88,90,93,94,97,99,101,102,112], which lead to improved efficiency, productivity, and human integration [84,85,88,89,91,92,97,98,112]. Even so, the integration of advanced robotic technologies requires significant support in terms of system redesign and implementation to avoid the infrastructure costs incurred, as well as system and process complexity [86,87,90]. To counteract this increase in complexity, advanced technologies such as wireless communication and Internet of Things (IoT) [84,88,99], Artificial Intelligence (AI) and AI agents [90,112], Cloud Computing [86], and HMI technologies [85,87,91,95,103] are employed, providing the necessary capabilities for data analytics and distribution, facilitating the operation of complex systems and the natural transition toward the framework of Industrial Metaverse [10]. This natural transition is a direct result of increasing demand for product customization [57,92,95,98], which leads to novel process scalability and material integration [101] and an increasing volume of automated sensitive tasks [19,57,58], which challenge the limits of flexible and collaborative robots in terms of precision and reliability, thus highlighting the need for collaborative human assistance in robotic processes [57,102]. While the integration of advanced digital technologies assists in these scenarios, concerns are raised concerning cybersecurity in the era of interoperability and communication [94,96,99].

Due to the diversity of challenges encountered during integration of robots and Cobots with human-centric manufacturing system, [17] proposed a taxonomy for robotic systems which considers Human-Robot Interaction (HRI) factors. This taxonomy categorizes HRI systems based on the roles of robots and humans, the robotic morphology and autonomy, and the nature of the HRI. The number of options considered by this taxonomy highlights the complexity of developing manufacturing systems based on Cobots. For example, gesture recognition could suffice for a passing or approaching proximity, which involves no physical contact, whereas a process necessitating contact proximity would require advanced voice recognition, as well as integrated direct-kill-switch capability bypassing other digital methods of communication. Most existing models of robotic autonomy fail to take collaboration capability into account, due to its dependency on the context of each collaborative HRI process. As such, HRI capability is separated from the ability to estimate its added value, which poses a significant roadblock to industrial integration [113].

5.4. Collaborative Human-Machine Interaction Model

Based on the Human-Machine Interaction (HMI) technologies, as well as the challenges and opportunities identified previously in this Section, a model for collaborative HMI is presented in Figure 5. The model describes the flow of information between humans and machines in the context of manufacturing systems and industrial collaboration, supported by the pillars of Industry 5.0 and the framework of Industrial Metaverse [10].

The controller of the robot, or any other machine humans interact with, is networked with integrated sensors and Extended Reality (XR) interfaces through the Internet of Things (IoT). Artificial Intelligence algorithms power data processing and decision-making processes using the data obtained by the integrated sensors, and the XR interface provides the human with the necessary information to perform tasks and make decisions in real-time. At the same time, sensor data is used to monitor human health, as well as human motion and machine proximity, ensuring safety from accidents and providing necessary support or instruction to maintain pristine working conditions. This general model can then be applied to specific situations, such as having the robot utilize the data from the wearable motion sensors to receive instructions via hand recognition, using its grip-mounted Flexible Pressure Sensor to perform precision maintenance operations on another machine, while an Augmented Reality (AR) device displays detailed maintenance instructions to the human, who can then provide the robot with the appropriate input.

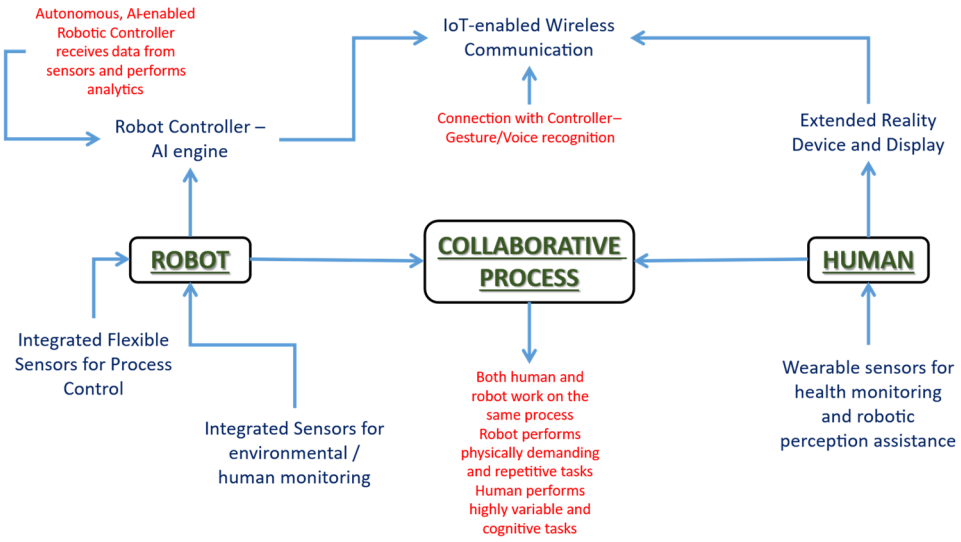


Figure 5. Collaborative Human-Machine Interaction Model.

5.5. Human-Machine Interaction development for industrial applications

It is important to consider that the conceptual model in Figure 5 does not describe the entire potential of HMI technologies. Table 2 summarizes TRL, major challenges, and notable trends of the three major HMI technological categories. It should be noted that average TRL is calculated based on the number of publications which can be assigned a TRL, meaning that review papers not describing a specific case study are not part of the calculation. A significant percentage of research on sensing systems is focused on providing the means supporting robotic perception development. However, as mentioned in Section 5.1, a majority of sensor developers do not integrate their research with manufacturing systems or the industry, meaning that the validation of sensor performance is limited to laboratory testing and that their potential for supporting robotics and XR applications has not been explored sufficiently. XR platforms could benefit from novel sensing systems with improved performance and reduced size, which would significantly reduce the weight of XR devices and improve their ergonomics while maintaining visualization fidelity. Similarly, the future of HRI is based largely on robotic perception, whether through gesture recognition with machine vision or voice command with audio perception. In this case, sensor size and flexibility are of lower importance. The major concern is sensor multifunctionality and performance. The goal is to reduce data traffic by reducing the number of channels feeding the control system and the number of different connections and protocols necessary for horizontal system integration.

Table 2. Challenges and trends for Human-Machine Interaction Technologies.

Technology	Avg TRL	TRL Range	Trends	Challenges
Sensors	3.76	3–4	Flexible sensors, multipurpose sensors, robotic perception, advanced materials, wearables	Mass production, industrial integration
Robotics	4.57	2–7	Collaborative robotics, soft robotics, machine vision	Human interaction, performance/flexibility ratio
XR	4.4	3–7	AR for human-machine collaboration and support, VR for training and simulation	Ergonomics/performance ratio, autonomy, fidelity

Through the integration of different technologies under the context of Industry 5.0 and the framework of Industrial Metaverse, the major challenge presented is the development of novel collaboration frameworks and techniques. Remote collaboration, simultaneous control and coordination of multiple operating machines, and human-machine collaborative process planning are but examples of applications being developed. This challenge can simultaneously be considered as an opportunity, since innovation gaps allow for dynamic entrance into this large and competitive market. A guide for the development of HMI technologies facilitating human-centric industrial applications can be found in Figure 6. The integration of collaborative processes is the main goal of HMI technology utilization in manufacturing. To achieve this integration, technological advancement is required both in the human and the robotic parts of HRI. Lightweight XR devices provide advanced control capabilities while multifunctional, flexible sensors embedded in clothing and robotic systems provide the necessary information for seamless communication. As such, in order to develop future HMI applications, it is important to invest in sensor and device development and integration.

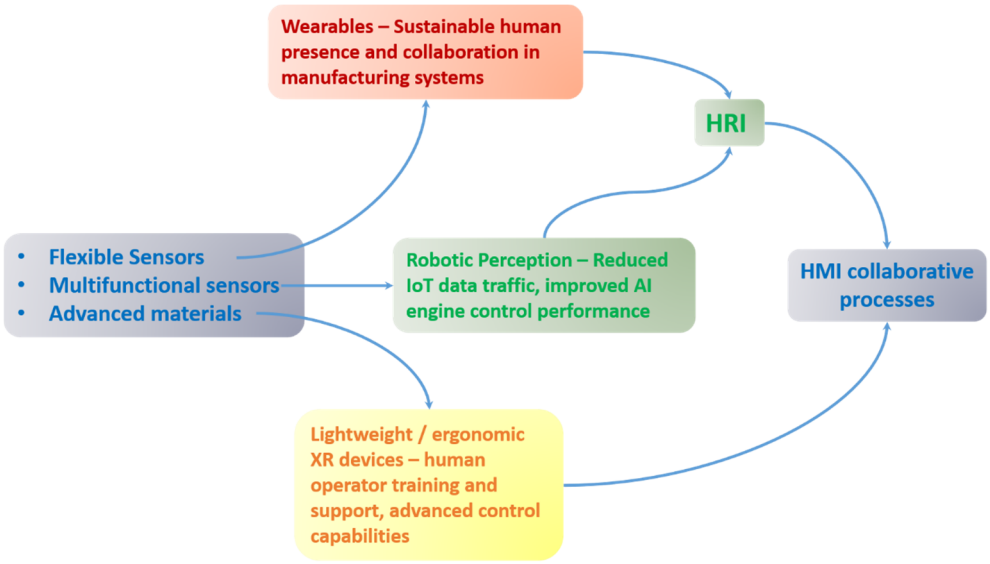


Figure 6. Development of Human-Machine Interaction technologies for industrial applications.

6. Conclusions

The future of manufacturing systems lies in Industry 5.0 and its pillars of human-centricity, sustainability, and resilience. The facilitation of these pillars leads to the globalized digital integration of manufacturing systems and the collaboration of advanced digital technologies, forming the architectural framework of Industrial Metaverse. Human-Machine Interaction (HMI) plays a major role in this context, as the role of humans in manufacturing systems is transitioning from supervisor to collaborator. HMI is supported by sensing technologies, mostly Flexible Sensors, Extended Reality (XR) devices and interfaces, and Collaborative Robots. These three layers of HMI form a symbiotic relationship, as sensing technologies allow robots to perceive their environment and operate autonomously, XR interfaces provide instructions and support decision-making for humans collaborating with robots, and robotic systems perform the advanced precision manufacturing processes necessary to develop advanced sensors and hardware used in XR devices. Several challenges have emerged concerning the feasibility, sustainability, and security of HMI, but the opportunities made available through this interaction counteract many of these challenges. Even so, great care must be taken during system digitalization to ensure that opportunities are exploited and challenges are overcome.

Prospects

In 2023, the World Economic Forum published a report on the top emerging technologies of that year. Among those technologies, a subcategory of neural electronics known as Brain-Machine Interfaces (BMI) made a significant impression. BMI is a specialized category of HMI which utilizes captured electrical signals of the brain and translates them into instructions for machines, facilitating direct brain-machine interface, which holds great potential for industries and the quality of human life [114]. BMIs are categorized as invasive, which means a device is inserted inside the human brain, and non-invasive, which utilize external sensors, usually Flexible Electroencephalography sensors, in coordination with a large variety of decoding algorithms which translate the signals for machines. Initially, these interfaces were unidirectional, from the brain to the machine, but since 2025 bidirectional communication has also been considered. Applications for BMIs include, among others, control of computer cursors, robotic arms, wheelchairs, and drones [115]. According to Gartner, about 30% of workers in knowledge-based jobs will be enhanced by some form of neurological implant by 2030 [9]. However, tampering with the human brain raises ethical concerns, which are currently being debated worldwide. The BRAIN Neuroethics Working Group (NEWG) held a meeting in 2025 where neurologists and biotechnology experts shared opinions on technical as well as ethical matters [116], and UNESCO has published its first draft providing recommendations on the ethics of neurotechnology [117]. In summary, the future of Human-Machine Interaction holds great potential, but both technical and ethical obstacles must be overcome before its realization.

Author Contributions

D.M.: Conceptualization, methodology, writing—original draft preparation, supervision, validation, writing—review and editing. D.T.: Conceptualization, data curation, methodology, writing—original draft

preparation, visualization, validation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

Given the role as Human-Machine Interaction Editorial Board Member, Dimitris Mourtzis had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A

Table A1. Challenges and Opportunities of Human-Machine Interaction technologies.

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Ultra-Sensitive and Linear Flexible Pressure Sensors with Tri-Scale Graded Microstructures for Advanced Health Monitoring and Robotic Perception	Flexible Pressure Sensors, Robotic Perception, Health Monitoring, Laser processing, Additive Manufacturing, roll-to-roll processing	Biological pressure variations, e.g., carotid artery or throat vibrations, remote operation of robotic hands	Sensor sensitivity and linear response Manufacturing long processing times, high equipment costs, throughput limitations		7	[18]
Research on the Digital Twin System of Welding Robots Driven by Data	DTs, Robots, Intelligent manufacturing	Data-driven digital twin of welding robotic arm, including advanced HMI	Development of digital communication technology, global industrial transformation	Internet of Things, improved production efficiency and capacity	5	[88]
HandMatic: Wireless Robotic Arm Control Using Real-Time Gesture Recognition for Seamless Human-Machine Interaction	Robotic Perception, Gesture Recognition, Health Monitoring, Manufacturing	Wireless robotic arm control through real time gesture recognition	Accuracy, latency, robustness, security, battery life	Wireless control for nuclear power plants, deep water drilling	5	[99]
Three-Dimensional Co-Printing of Hydrogels and Elastomers for Facile Fabrication of Soft Electronics and Robotics	Soft Electronics and Robotics, Materials	Fabrication of sensors and integrated robotic systems using hydrogels and elastomers	Process scalability, material integration	Multi-material additive manufacturing	6	[101]
Applying social robotics principles to B2B manufacturing mobile robots to design new ways of working	Social Robotics, Mobile Robots	Development of a collaborative robot for workplace assistance and human interaction	Modern workplace flexibility requirements, skepticism, job displacement, human agency	Agentive technology, workflow redesign, productivity, safety	4	[112]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Zero-shot autonomous robot manipulation via natural language	Robotic Perception, Natural Language	Zero-shot robot manipulation through natural language	Deep Learning model data preparation, training, adaptation	Generative Pre-trained Transformers, Large Language Models	4	[100]
Development, Experimental, and Numerical Characterisation of Novel Flexible Strain Sensors for Soft Robotics Applications	Flexible Strain Sensors, Soft Robotics, Limb rehabilitation, fragile object gripping, HMI	Flexible sensors produced through additive manufacturing	Sensitivity of robotic operation in health and agriculture		3	[19]
Constructing Reconfigurable and Affordable Robotic Arm Platform to Teach Robotics and Automation	Learning Robots	Development of reconfigurable robotic arm platform for engineer training	Need for skilled engineers	Hands-on experiences	7	[83]
Collaborative robots in manufacturing and assembly systems: literature review and future research agenda	Cobots	Review	Product customization, time-to-market, job security	Improved work conditions, safety, flexibility	-	[92]
Target-following Robotic Platform Based on UWB Localization and Depth Camera	Robotic Perception	Development of robot capable of following a set target using Ultra-Wideband technology and cameras	Dynamic environments and goals, human presence	Integrated multi-purpose sensors and control systems, following and assisting humans	4	[84]
Design and Control Scheme Of A Rigid-flexible Coupled Duel-arm Hug Robots	Humanoid Robots	Rigid-flexible coupled dual-arm Robot for human-robot interaction	Low flexibility-capacity ratio and safety of rigid robots, fatigue and deformation of flexible robots	Enhanced safety and collaboration	4	[102]
A safety-enhancing framework based on collaborative robots (CoBot) for Industry 4.0	Cobots	Camera and ultrasonic sensors for calculation of distance between robot and operator	Lack of integrated systems in traditional robotics, safety standards	Safety, streamlined workflows, versatility	4	[93]
Human-Machine Interaction Systems for Training Industrial Robots	Learning Robots	Evaluation of Reinforcement and Imitation Learning (RLIL), Vision-based Task Recognition and Execution (VITREX), Natural Language Command Processing with Contextual Feedback (NLCCF)	Manufacturing flexibility and adaptability demands	Safety, productivity, versatility, robot training through HMI	3	[85]
An Overview of the Untapped Potential of Soft Robotic Arms with Integration of Machining Tools	Soft Robotics	Design of soft robot drilling arm	Product customization and fragility, gravity slacking	Biomimicry, flexibility in dynamic environments	-	[57]
Research on Guidance Methods of Digital Twin Robotic Arms Based on User Interaction Experience Quantification	DTs, Robots	Virtual interaction of Digital Twin robotic arms	Execution time, deviation, reliance on operator	Efficiency for convoluted tasks	4	[89]
Software framework concept with visual programming and digital twin for intuitive process creation with multiple robotic systems	DTs, Robots	Human-centered software framework for multiple systems and processes	Increased usage of complex robotic systems in intralogistics and production, high cognitive load, program synchronization, worker training	Collaboration capabilities, intelligent operator assistance	6	[90]
Collaborative Robots and Cyber Security in Industry 5.0	Cobots	Review	Cybersecurity	Increased productivity, safety, flexibility	-	[94]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Towards a Cloud-Controlled Heterogeneous Robot System Based on Microservices	Cloud, Robots, Unmanned Operations, extra-terrestrial applications	Cloud-controlled heterogeneous robot system based on microservices	Demand for complex robots, data structures, operational logic	Cloud Technology, automation,	6	[86]
Collaborative Robots for Smart Production in SMEs	Cobots	Review	Customer demands, customization, fast adaptation, reconfiguration	Automation enabled by HMI	-	[95]
Challenges in the Safety-Security Co-Assurance of Collaborative Industrial Robots	Cobots	Review	Safety, cybersecurity, ethics		-	[96]
Agile Visual Programming of a Multi-robot Cyber-Physical System with Operator Interaction	DTs, Robots	Virtual programming of multi-robot system for assembly processes	System complexity, programming times and requirements	Virtual technologies, advanced network interfaces, efficiency	3	[91]
Programming Robots by Demonstration Using Augmented Reality	AR, Robots	Enabling an industrial operator without any programming experience to program a robot	Task cost and complexity	HMI through Augmented Reality	3	[87]
A Cable-Driven Switching-Legged Inchworm Soft Robot: Design and Testing	Soft Robotics	Cable-driven switching-legged inchworm-inspired soft robot	Fragile product manipulation	Biomimicry	4	[58]
Methodology for the definition of the optimal assembly cycle and calculation of the optimized assembly cycle time in human-robot collaborative assembly	Cobots	Task scheduling identifying the optimal assembly cycle	Support required for system redesign and technology implementation	Safety, flexibility, working conditions	7	[97]
MEGURU: a gesture-based robot program builder for Meta-Collaborative workstations	Robotic Perception, Gesture Recognition, Cobots	Complex robot commands via combination of single-hand gestures	Automation and customization, production rate to flexibility ratio	Collaboration for manual processes	5	[98]
Mechatronic Systems Design of ROHNI-1: Hybrid Cyber-Human Medical Robot for COVID-19 Health Surveillance at Wholesale-Supermarket Entrances	Health Monitoring, Humanoid Robots	Hybrid Cyber-Human Medical Robot for Health Monitoring	Globalization of epidemics, system resilience	Humanoid robotics, HMI	2	[103]
Wafer-level high performance MIM humidity sensor based on nanofiber-microcavity hierarchical structures	Humidity Sensors, Materials, Environmental monitoring, health monitoring	Humidity sensor based on nanofiber-microcavity hierarchical structures	Manufacturing scalability		3	[53]
Design of a high-performance flexible pressure sensor based on AgNWs-MXene/MWCNTs composites and its multi-scenario application study	Flexible Pressure Sensors, Materials, Wearables	Design of a high-performance flexible pressure sensor based on AgNWs-MXene/MWCNTs composites	Robustness, flexibility		4	[20]
Sequentially squeezed capacitive pressure sensor based on baguette-inspired porous ionic gel foams	Flexible Pressure Sensors, Materials, Health monitoring	Capacitive pressure sensor based on porous ionic gel foams	Sensitivity, detection range, cost		4	[21]
Flexible humidity sensors for diverse applications	Humidity Sensors	Health monitoring, agriculture, smart homes	Precision, multifunctionality, autonomy	Material and process innovation	-	[54]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Hierarchically structured dual-mode sensor with directional moisture-wicking capability for weak physiological signal monitoring and long-range motion tracking	Flexible Sensors, Health Monitoring, Wearables	Composite flexible sensor supporting contact and non-contact sensing	Population aging, comfort, accuracy, multifunctionality		3	[22]
Recent Progress in High-performance Flexible Pressure Sensors: Materials, Design, Fabrication, and Applications	Flexible Pressure Sensors, Materials	Health monitoring, electronic skin, Artificial Intelligence	Material selection, microstructure	Material and process innovation	-	[23]
Preparation, Integration, and piezoresistive performance of MXene materials for multifunctional pressure sensor design	Flexible Pressure Sensors, Materials	MXene pressure sensors	Scalability, implementation	Widely applicable	-	[24]
Porous pressure sensors from mechanisms to application: A review	Flexible Pressure Sensors	Porous structure sensors, health monitoring, robot control, electronic skin	Multifunctionality, safety, modeling, applicability	Market potential, diversification	-	[25]
High-resolution 3D printed strain sensor with superb stretchability and sensitivity: Unveiling the potential of melt electrowriting	Flexible Pressure Sensors, Materials, Human motion detection, health monitoring	Structure optimization via melt electrowriting	Sensitivity-stretchability ratio		4	[26]
A new design of an electromyography sensor for movement detection in human-machine interaction systems	Electromyography Sensors, Health Monitoring	Electromyography sensor for movement detection	Robustness	Cost	4	[48]
AI-Enhanced Materials Identification with Smart Directional Tangential Flexible Sensor	Tangential Flexible Sensors, AI, robotic arms, material and texture recognition	Flexible sensor with anisotropic micro-pillar structure	Multi-axis sensing	Artificial Intelligence integration	4	[41]
Textile-based interdigitated electrode piezoresistive sensor: Materials, fabrication and applications—A review	Flexible Pressure Sensors, Materials, Wearables, Sensor Integrated Textiles	Health monitoring, electronic skin, piezoresistive sensors	Adhesion, durability, robustness	Artificial Intelligence integration	-	[27]
Neural network-assisted carbon nanotube hydrogel-based dual-modal sensors for material perception	Hybrid Sensors, Materials, AI	High-performance proximity/pressure dual-modal sensor	Production streamlining	Artificial Intelligence integration	3	[59]
Fully Flexible Vibration Sensor based on Suspended Membrane with Metal Microcracks	Flexible Vibration Sensors, Materials	Flexible Vibration Sensor based on Suspended Membrane with Metal Microcracks	Brittleness, weight, installation	Health monitoring, diagnostics	4	[42]
Recent Advances of Flexible Pressure Sensors: A Review	Flexible Pressure Sensors	Materials and processes	Sensitivity-range ratio, material compatibility	Biocompatibility, flexibility	-	[28]
Design and Development of a Flexible Inductive Bend Sensor Using Planar Meander Coil Topology	Flexible Bending Sensors	Flexible Inductive Bend Sensor Using Planar Meander Coil Topology	Practicality, robustness	Sensitivity, interference immunity	4	[43]
Deep learning-assisted object recognition with hybrid triboelectric-capacitive tactile sensor	Tactile Sensor, AI	Object recognition with hybrid triboelectric-capacitive tactile sensor	Accuracy	Robotic intelligence	4	[50]
Bioinspired, fiber-based, flexible self-powered sensor for wearable applications	Flexible Sensors, Wearables	Flexible self-powered sensor for wearable applications	Adaptability, sensitivity, scalability	Process innovation	4	[46]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Multi-walled carbon nanotube-enhanced polyurethane composite materials and the application in high-performance 3D printed flexible strain sensors	Flexible Pressure Sensors, Materials, wearables, motion detection	Thermoplastic polyurethane/ multi-walled carbon nanotube flexible pressure sensors	Material and process selection	Material and process innovation	4	[29]
Preparation and performance of biaxially stretched CNT-SBS/POE flexible strain sensor with a double percolation structure	Flexible Pressure Sensors, Materials, wearables, health monitoring	flexible pressure sensor with a double percolation structure	Range-sensitivity ratio	Robustness	4	[30]
3-D Printed Fourth-Order Star-Like Negative Poisson's Ratio Structure for High-Sensitivity Bionic Flexible Capacitive Pressure Sensor	Flexible Pressure Sensors, Wearables, Materials	High-Sensitivity Bionic Flexible Capacitive Pressure Sensor	Performance, cost	Multi-axis sensing, biomimicry	3	[31]
A Flexible Pressure Sensor with Wide Detection Range Based on Capacitive-Piezoresistive Dual Mode Conversion for Human-Machine Interaction	Flexible Pressure Sensors, Health monitoring	Capacitive-Piezoresistive Dual Mode Conversion flexible pressure sensor	Range-sensitivity ratio, cost, robustness	Process innovation	4	[32]
Recrystallization-Induced Laser Lift-Off Strategy for Flexible Thermal Sensors with Near-Limit Sensitivity	Flexible Thermal Sensors, Health monitoring	Flexible Thermal Sensors with Near-Limit Sensitivity	Sensitivity, robust manufacturing process	Process innovation	4	[45]
Recent advances in flexible bending sensors and their applications	Flexible Bending Sensors, Health monitoring, soft robotics, motion detection	Applications	Interference, adaptability, multi-axis sensing		-	[44]
Improving Soft Capacitive Tactile Sensors: Scalable Manufacturing, Reduced Crosstalk Design, and Machine Learning	Tactile Sensors, AI, Wearables, soft robotics	Parallel plate soft capacitive sensor array	Scalability, safety	Artificial Intelligence integration	4	[51]
Flexible, Breathable and Sweatproof Piezoelectric Sensors based on Additive Manufacturing	Flexible Pressure Sensors	Composite flexible piezoelectric sensors	Assembly processes	Additive processes	3	[33]
Highly Flexible and Sensitive Proximity Sensor Based on Liquid Metal Microfluidic Fibers	Proximity Sensors, Materials, robotic arm control	Flexible capacitive proximity sensor	Natural interaction	Material innovation	4	[55]
Hybrid 3D printed three-axis force sensor aided by machine learning decoupling	Force Sensors, AI	Hybrid 3D printed three-axis force sensor	Assembly processes, testing	Artificial Intelligence integration	5	[60]
Template-free Formation of Hybrid Dielectric for Flexible Capacitive Sensors with Wide-Pressure-Range Linear Detection	Flexible Pressure Sensors	Flexible Capacitive Sensors with Wide-Pressure-Range Linear Detection	Production processes, robust information transmission, cost	Biomimicry	4	[34]
A dual-mode fiber-shaped flexible capacitive strain sensor fabricated by direct ink writing technology for wearable and implantable health monitoring applications	Flexible Pressure Sensors, Wearables, Health Monitoring	fiber-shaped flexible capacitive strain sensor	Stretchability	Process innovation	4	[35]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Morphological Engineering of Sensing Materials for Flexible Pressure Sensors and Artificial Intelligence Applications	Flexible Pressure Sensors, Materials, AI, Health monitoring, smart homes, security	Self-assembly, patterning, auxiliary synthesis	Material/structure innovation, sensitivity, range, robustness, multi-axis sensing	Artificial Intelligence and Internet of Things integration	-	[36]
Fabrication method of flexible strain sensors with CNTs and solvents	Flexible Pressure Sensors, Materials, Motion detection	Flexible carbon nanotube sensor	Material selection		3	[37]
Multimode human-machine interface using a single channel and patterned triboelectric sensor	Triboelectric Sensors	Single-channel and patterned triboelectric sensor	Structure	Sustainability, cost, diversification	4	[52]
Investigation of stretchable strain sensor based on CNT/AgNW applied in smart wearable devices	Flexible Pressure Sensors, Materials, Wearables, Health monitoring, motion detection	Smart glove, comprises a sensor array and a flexible, printed circuit board	Durability, responsiveness		4	[38]
Magnetic flexible sensor with tension and bending discriminating detection	Flexible Hybrid Sensors	Magnetic flexible sensor with tension and bending discriminating detection	Multifunctionality, cost	Process innovation	4	[64]
Printed Strain Sensors for On-Skin Electronics	Flexible Pressure Sensors, Health Monitoring, motion detection, electronic skin, rehabilitation, robotics	Review	Material, structure, process innovation and suitability		-	[39]
Flexible strain sensors: from devices to array integration	Flexible Hybrid Sensors	Flexible sensor arrays	Stretchability, interconnectivity, robustness, cost	Process innovation	3	[65]
Prospects of Wireless Energy-Aware Sensors for Smart Factories in the Industry 4.0 Era	Wireless Sensors	Industrial Wireless Sensor Networks	Energy consumption	Performance, logistics management, prediction, ergonomics	-	[56]
Self-Powered Miniaturized Acceleration Sensor Based on Rationally Patterned Electrodes	Acceleration Sensors, Industry, biology, navigation	Miniaturized acceleration sensor	Passive sensing, range, size, cost		3	[49]
Recent Progress in Printed Physical Sensing Electronics for Wearable Health-Monitoring Devices: A Review	Sensors, Wearables, Health Monitoring	Health monitoring, wearables	Performance, material and structure selection	Rapid advancement, cost, production rate, diversification	-	[47]
Augmented Reality-enabled visualization and process control in 3D printing and Additive Manufacturing	AR, Additive Manufacturing	Technology acceptance model for AR in Additive Manufacturing	Manufacturing downtime, energy consumption, quality Field of view, latency, data exchange	Real-time visualization and decision-making	-	[70]
Enhancing yield and process efficiency through dual internet of things and augmented reality for AI-driven human-machine interaction in centering mass production	AR, AI	AR and Internet of Things HMI Manufacturing System	Human dependence	Efficiency, productivity	5	[61]
Human-Centric Green Design for automatic production lines: Using virtual and augmented reality to integrate industrial data and promote sustainability	AR, VR, Sustainability	AR and VR Digital Twin	Sustainability, complexity, usability, accessibility, comfort	Rapid advancement	7	[66]
A User-Centric AI-Enhanced Approach to AR frameworks in Manufacturing	AR, AI	User-Centric AR applications with vision systems driven by Artificial Intelligence	Intuitive interaction	Smart interfaces, Artificial Intelligence integration	4	[62]

Table A1. *Cont.*

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Digital toolkit for human-centered machine design: development and testing of an innovative system integrating virtual reality and HMI digital prototypes	VR	VR and desktop application simulating HMI	HMI efficiency, human-centric design	Virtual interaction, real-time visualization	7	[67]
Step Into Context: Location-Aware AR Feedback for Smart Manufacturing Using Low-Cost Hardware	AR	Ultra-Wideband location specific machine data delivery	Spatial awareness, interconnectivity	Sensor integration	4	[71]
Enhancing automated production lines with human-centricity: how to combine virtual reality simulation and human data analysis	VR, Data	VR simulation and wearable devices for motion detection and health monitoring	Maintenance, process control, cognitive ergonomics	Human skill integration with advanced technologies	4	[68]
Enhancing metal additive manufacturing training with the advanced vision language model: A pathway to immersive augmented reality training for non-experts	AR, Additive Manufacturing, AI	Digital Twin training system using Visual Language Modeling and AR	Conventional training methods	Immersion, interaction, Artificial Intelligence integration	4	[63]
An innovative AR-assisted self-adjusting digital twin for speed control of a servomechanism	AR, DTs	AR assisted self-adjusting Digital Twin	Process degradation	Visualization	4	[72]
Context-Aware Recoloring Approach for AR-Assisted Maintenance Applications	AR, Maintenance	AR content recoloring	Maintenance, dynamic conditions	Visualization modality	4	[73]
Not Lost In Translation—Spatiotemporally-Aligned Human-Machine Interfaces Through IoT-Integrated Augmented Reality	AR	Spatiotemporally aligned Human-Machine Interfaces	Interface clutter, inconsistency, and physical object mapping	Internet of Things integration	4	[74]
Developing Design Guidelines For Augmented Reality Applications As Operating Assistance For Manufacturing Machines	AR	AR operational worker support	Production cost, time, quality, unskilled workers	HMI efficiency and effectiveness	4	[75]
Application of Augmented Reality to Support Manufacturing Resilience	AR, Resilience	Augmented resilient human worker	Globalization disruptions (pandemic, sociopolitical events), resilience	Digitalization, autonomy	-	[76]
Evaluating Digital Assistance in Form of Augmented Reality for Manual Processes in the Metal Binder Jetting Process Chain	AR, HUD	Metal Binder Jetting AR assistance	Divided manual processes, skill requirements	Visualization, quality improvement	4	[77]
Head-mounted display augmented reality in manufacturing: A systematic review	AR, HUD	Heads-Up Display	Ergonomics, cognitive load, synchronization	Visualization, immersion, mobility	-	[78]
A state-of-the-art survey on Augmented Reality-assisted Digital Twin for futuristic human-centric industry transformation	AR, DTs	AR assisted Digital Twin in Manufacturing	Process and service design and optimization	Human integration	-	[79]

Table A1. *Cont*.

Title	Field of Application	Objective	Challenges	Opportunities	TRL	Reference
Design, testing and control of a smart haptic interface driven by 3D-printed soft pneumatic actuators for virtual reality-based hand rehabilitation	VR, Haptics, Health Monitoring	Hand rehabilitation based on haptics and VR interface	Rehabilitation, estimated motion prediction	Soft material additive manufacturing, health monitoring	3	[40]
Augmented reality-based guidance in product assembly and maintenance/ repair perspective: A state of the art review on challenges and opportunities	AR, Maintenance	AR in assembly, disassembly, and maintenance	Knowledge transfer	Rapid technological advancement, immersion, flexibility	-	[80]
Intelligent human-machine interaction based on digital twin and virtual reality	VR, DTs	Intelligent multi-axis robot arm, object recognition	Applicability, cooperation	Artificial Intelligence and Digital Twin integration	3	[69]
Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review	AR, VR	Review	Mass customization, AR and VR hardware and software	Immersion, flexibility, design, maintenance, management, quality	-	[81]
Design and Development of Smart Campus using Augmented Reality(SCAR)	AR	Smart Campus AR mobile application	Daily assistance	Automotive, health monitoring, robotics, education	5	[82]

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