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How Cognitive Capabilities for Smart Operator enhance Human-Robot Collaboration

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Abstract

The concept of the Smart Operator, or Operator 4.0, signifies a transformative era in industrial settings where human workers leverage advanced technologies to enhance productivity, efficiency, and collaboration. This paradigm shift recognizes the importance of integrating automation and intelligent technologies with human intelligence and problem-solving skills. A variety of cognitive talents that are strengthened by cutting-edge technology are beneficial to the Smart Operator. This paper explores the realm of cognitive capabilities and how these can be addressed in human-robot collaboration contexts in order to enhance Smart Operator performances by emphasizing the role of technologies belonging to the Industry 4.0 domain, such as environmental sensors, cloud computing, simulation, virtual reality, artificial intelligence, and big data analytics. Throughout this document, the authors investigate the individual technologies enabling cognitive capabilities and analyze their impacts on human-robot collaborative contexts. The paper also highlights research studies investigating the impact of these technologies on operator performance. Moreover, this paper proposes a flexible and scalable framework for smoothly integrating cognitive skills by producing a Digital Twin of actual physical systems and procedures. By leveraging these cognitive capabilities enhancing technologies, the Smart Operator paradigm paves the way for a future where intelligent machines and human ingenuity harmoniously coexist, driving innovation and success in collaborative industrial environments.

Keywords: Smart Operator; Cognitive Capabilities; Human-Robot Collaboration; Industry 4.0;

1. Introduction

The introduction of the Smart Operator, also known as Operator 4.0, heralds a new age in industries brought about by the quick development of technology. By utilizing cutting-edge technologies and cognitive abilities to improve productivity, efficiency, and collaboration in industrial settings, this concept marks a paradigm shift in the role of human workers. According to Longo et al. (2017), the Smart Operator is a highly trained operator who is outfitted with cutting-edge tools and integrated systems that enable them to excel at complicated jobs while collaborating with robotic counterparts.

The Smart Operator symbolizes how traditional industrial workers have changed to meet the demands of the modern digital era. This concept acknowledges the intrinsic significance of human intelligence, flexibility, and problem-solving skills. The Smart Operator uses technology to enhance their cognitive capacities and drive performance rather than being only a passive recipient of instructions in the industrial ecosystem (Di Pasquale et al., 2021).

The Smart Operator possesses a diverse range of cognitive capabilities that synergize with technological advancements. The cerebral functions and abilities that allow humans to perceive, comprehend, retain, and apply information are referred to as cognitive abilities. They encompass a diverse array of cognitive functions that are closely related and harmoniously shape human perception of the world, direct our behavior, and support our social relationships (Helfat & Peteraf, 2014). Cognitive Capabilities are:

- Perception: mental activities or processes "that organize information (in the sensory image) and interpret it as having been produced by properties of (objects or) events in the external (three-dimensional) world" (American Psychological Association, 2009).
- Attention: a state of focused awareness on a subset of available perceptual information (American Psychological Association, 2009).
- Problem Solving: thinking that is directed toward solving specific problems and that moves from an initial state to a goal state by means of mental operations (American Psychological Association, 2009)
- Reasoning: evaluating information, arguments, and beliefs to draw a conclusion or using the information to determine if a conclusion is valid or reasonable (Gazzaniga et al., 2010)
- Language and Communication: there is no universally accepted definition of "language" in psychology. The term is sometimes used broadly to indicate "any system for representing and communicating ideas" (Kolb and Whishaw, 2009).
- Social Cognition: perceiving, attending to, remembering, thinking about, and making sense of the people in our social world (Moskowitz, 2005).

The industrial sector has been actively pursuing the combination of technology and human capability because it wants to increase operational effectiveness while preserving the priceless abilities and insights that people bring to the table. Smart operators flourish in complex and demanding work contexts because they have a great set of cognitive skills.

The technologies that enhance cognitive capabilities in the context of smart operators encompass a range of innovative tools (Gazzaneo et al., 2020), such as:

- Environmental Sensors.
- Cloud computing.
- Simulation.
- Virtual Reality (VR).
- Artificial Intelligence (AI).
- Big data Analytics.

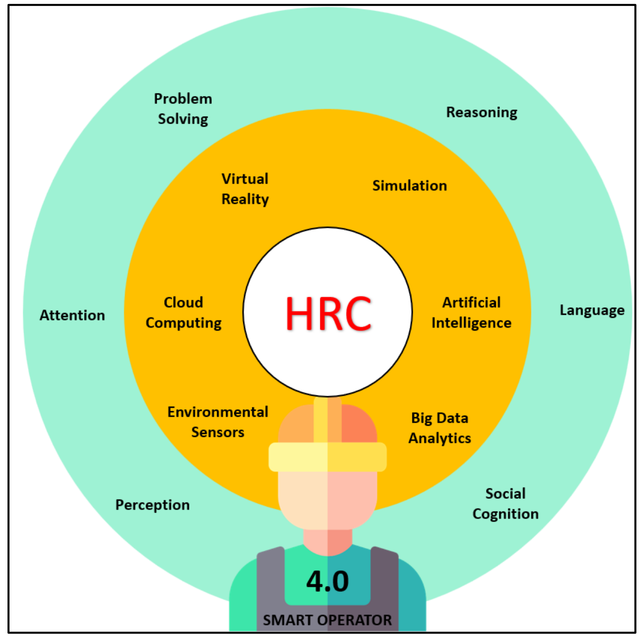

Figure 1. Cognitive Capabilities enabling technologies for HRC

In the ever-evolving landscape of industry, the convergence of cognitive capabilities and the rise of smart operators paved the way for advancements in human-robot collaboration (HRC). At the core of this transformative synergy lies the extraordinary cognitive abilities exhibited by smart operators. Equipped with advanced skills in critical thinking, adaptability, and problem-solving, these operators can harness their cognitive prowess to seamlessly integrate with robotic systems. Figure 1 represents the full compass of the integration of Cognitive Capabilities, Industry 4.0 technologies and HRC for the Smart Operator. The resulting collaboration between humans and robots transcends traditional boundaries, creating a dynamic partnership that optimizes productivity, efficiency, and safety within industrial environments. On the other hand, Figure 2 represents the links between all cognitive capabilities with the new paradigm industrial technologies and the links between these new technologies and the application domains of HRC scenarios. By capitalizing on the unique strengths of both humans and robots, this paradigm shift in HRC is reshaping the industrial landscape and propelling us towards a future where intelligent machines and human ingenuity work hand-in-hand to unlock new levels of innovation and success.

Throughout this document, the authors investigate the individual technologies enabling cognitive capabilities and analyze their impacts on human-robot collaborative contexts. The remainder of the paper is structured as follows: Section 2 is focused on the state of the art regarding the existing studies related to Smart Operators and their Cognitive Capabilities

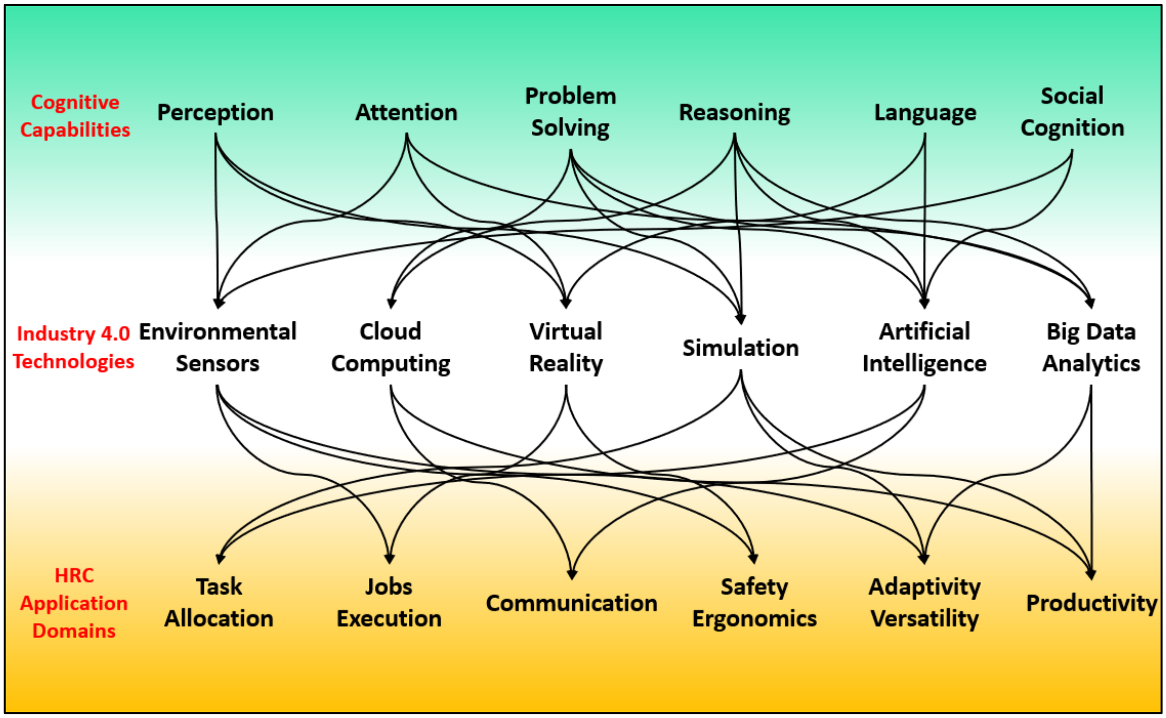

Figure 2. Correlation between Cognitive Capabilities – Industry 4.0 Technologies – Human-Robot Collaboration

enhanced by Industry 4.0 technologies in HRC scenarios. Section 3 deals with the analysis of the relationship between the Cognitive Capabilities and the technologies of Industry 4.0 with respect to Smart Operators in HRC. Finally, section 4 is focused on a high-level digital twin-based framework involving the integration of the said technologies for enhancing Cognitive Capabilities in HRC.

2. State of the art

In the domain of HRC, the integration of cognitive capabilities and Industry 4.0 technologies has opened up new frontiers for enhancing performance, efficiency, and user experience. The recent literature encompasses diverse areas such as the influence of Collaborative Robots (Cobots) on operator performance, the role of Visual Computing technologies including Augmented Reality (AR) and Virtual Reality (VR), the analysis of human factors and cognitive load, and the importance of user experience (UX) and interface design in facilitating effective collaboration. Through an examination of these topics, it is possible to gain valuable insights into the evolving landscape of HRC and its implications for various industrial domains.

A significant body of research has focused on the integration of cognitive capabilities and technologies in the realm of HRC. For instance, De Simone et al. (2022) conducted a study to assess the impact of cobots on operator performance. They identified key factors, including stress, workload, acceptance, trust, and usability, that influence the collaborative operator's effectiveness. Similarly, Manns et al. (2021) proposed a spatial region-based approach that utilizes real-time simulation to understand human operators' intentions and predict their activity sequences in collaborative environments improving perception, job execution and language. This approach has the potential to enhance the overall understanding of human actions and improve collaborative interactions between humans and robots.

In the context of Industry 4.0, Visual Computing technologies such as AR and VR have emerged as pivotal tools. These technologies, alongside advanced Computer Vision and Human-Computer Interaction techniques, play a crucial role in enhancing HRC. Posada et al. (2021) presented a theoretical framework that incorporates Visual Computing and Physically-based Simulation technologies into Industry 4.0 and Operator 4.0 scenarios. This framework envisions a future where intelligent machines and human operators work together, leveraging augmented reality, VR, and simulation to enhance collaboration and optimize performance potentially improving attention, perception and reasoning. Papcun et al. (2019) proposed an Augmented Reality (AR) environment for storekeepers, enabling them to visualize the planned path of Automated Guided Vehicles (AGVs) and add virtual obstacles and walls to guide the navigation of mobile robots. This system architecture supports safe and productive interaction between humans and mobile robots by defining restricted areas and providing a visual representation of safe zones for stationary work supporting attention and perception in collaborative contexts.

Furthermore, research has emphasized the importance of understanding human factors and cognitive load (intend as the effort required by the human operator in terms of attention, perception and reasoning) in collaborative environments. Fruggiero et al. (2020) conducted a simulated analysis of a collaborative work cell in the automotive sector, quantifying the cognitive load and investigating various interaction factors such as age, interface complexity, and recovery strategies paving the way for interesting observation regarding attention, perception and task allocation in collaborative contexts. Di Pasquale et al. (2022) focused on Human-Reliability Analysis (HRA) methods in the context of HRC in production systems. They aimed to define a taxonomy of Performance-Shaping Factors (PSFs) that can be utilized to evaluate Human Error Probability (HEP) in collaborative environments. By considering these factors, researchers strive to improve the performance and reliability of HRC by addressing cognitive capabilities and mitigating the occurrence of human errors.

In the design of effective human-robot collaborative systems, attention has been given to user experience (UX) and interface design. Khamaisi et al. (2021) highlighted the need for reliable and systematic user-centered methodologies to design Augmented Reality (AR) applications for human-robot collaborative tasks. They emphasized the importance of reducing cognitive workload, interface simplification, and usability tests to enhance the acceptance and integration of AR technologies within the Operator 4.0 paradigm. Materna et al. (2017) focused on the concept of spatial augmented reality (SAR) and its potential to enhance usability and minimize attention switching during demanding tasks.

Overall, these research studies highlight the ongoing efforts to integrate cognitive capabilities, advanced technologies, and human factors in the pursuit of effective HRC. By understanding the impact of these factors, researchers aim to optimize performance, reliability, and user experience, ultimately shaping the future of collaborative environments in various industrial domains.

3. Cognitive Capabilities in Human-Robot Collaboration

This section explores the cognitive capabilities domain and the integration possibilities through the Industry 4.0 domain technologies, including cloud computing, simulation, VR, AI, and big data analytics, into HRC. It investigates how these capabilities can positively impact collaborative environments, highlighting their benefits.

In this section, a sub-paragraph is dedicated to each cognitive capability identified in section 1, namely perception, attention, problem solving, reasoning, language, and social cognition.

3.1. Perception

In the authors' view, perception can be defined as the cognitive ability to process and understand sensory data from the surrounding world in the context of HRC. In order to make wise decisions and complete tasks successfully, one must have the capacity to notice and comprehend pertinent cues, objects, and events. To maximize productivity and safety in the dynamic realm of HRC, improving human perception is essential.

An operator's perspective can be considerably enhanced by a well-designed workspace. Operators may concentrate on their work without being distracted by unneeded distractions by offering an ergonomic and tidy workspace. Effective job allocation and execution are supported by good illumination, noise reduction, and comfortable workstations, which all enhance perception. The operator's perception is improved by integrating cutting-edge environmental sensors into the collaborative workplace. Real-time data on a variety of variables, including temperature, humidity, air quality, and even the presence of dangers, can be provided by these sensors. With this knowledge, operators may make more intelligent choices and give ergonomics and safety-first priority when performing tasks (Kamble et al., 2018).

A powerful tool for enhancing perception and flexibility in collaborative settings is simulation paired with VR. Operators can practice without risk by providing virtual reproductions of challenging situations and collaborative activities (Matsas & Vosniakos, 2015). This routine helps them see possible problems more clearly and makes it easier for them to react appropriately, resulting in more efficient work allocation and execution.

Environmental sensors give real-time information for enhanced decision-making, notably in areas of safety and ergonomics, while a well-designed work environment stimulates focused attention. Additionally, by allowing the operator to engage in a variety of collaborative scenarios and improve their understanding of key elements of the duties, simulation increases their adaptability and versatility.

3.2. Attention

According to the authors, attention can be defined as the cognitive ability to focus on particular tasks, events, or information while excluding distractions when referring to HRC. For efficient task completion and successful communication in a collaborative environment, operators must maintain high levels of attention. In this collaborative setting, utilizing the most appropriate technology can greatly enhance an operator's focus.

VR is notable technology to improve attention. VR attracts operators' attention by placing them in lifelike simulated worlds, allowing them to perform difficult jobs without taking any real-world risks. This increased engagement encourages prolonged focus and sharpens operators' skills and can result in more effectively completed tasks (Matsas & Vosniakos, 2015).

An important factor in maximizing attentional resources is big data analytics. Operators can make data-driven decisions by analyzing and interpreting the massive amounts of data generated during cooperation (Lu, 2017). This gives individuals the ability to focus their attention on important tasks in an efficient manner, increasing task allocation, task execution, and overall efficiency. Moreover, a well-designed workspace also has ergonomic workstations and reduces distractions and unneeded noise. Operators are better able to maintain their focus by minimizing distractions, which improves work execution and safety (Kamble et al., 2018).

In the context of HRC, VR, big data analytics, and a well-designed work environment can improve human attention. By encouraging long-term participation and skill development, offering on-demand assistance with information management, and facilitating data-driven decision-making, operators may focus more intently and, as a result, promote a more fruitful and effective collaborative relationship with robots.

3.3. Problem Solving

Problem-solving, in the authors' view, in the context of HRC refers to the cognitive ability to recognize obstacles, evaluate circumstances, and come up with workable solutions to deal with challenging tasks and concerns. In collaborative environments, it is essential for maximizing task distribution, job execution, communication, ergonomics and safety, adaptability, and overall efficiency.

Access to a huge variety of data, historical information, and real-time changes is made possible via cloud-based services. Human operators may make knowledgeable decisions and use a plethora of knowledge to efficiently address problems by utilizing cloud computing (Armbrust et al., 2010). Access to a variety of information sources encourages flexible problem-solving and facilitates efficient job allocation and execution. A valuable tool for developing problem-solving abilities in a safe environment is simulation technology (Malik & Bilberg, 2018). Operators can practice handling a variety of difficulties that might appear during collaboration by running through simulations. This training improves problem-solving versatility and quick thinking, which is advantageous for job performance and general safety.

AI can also change problem-solving by analyzing massive data sets and spotting patterns or trends that human operators might not notice right away. With the aid of AI-powered algorithms, difficult situations may be quickly assessed, solutions can be suggested, and better decisions can be made when assigning tasks and carrying them out (Huang et al., 2021).

Operators may be able to derive useful insights from the vast quantities of data created during HRC by integrating big data analytics. Operators can use this information to find potential bottlenecks, foresee potential dangers, and increase efficiency. The effectiveness and efficiency of collaboration are increased by data-driven issue-solving (Zhong et al., 2017).

The potential of Cloud Computing, Simulation, AI, and Big Data Analytics may be fully utilized by human operators in collaborative situations to dramatically improve their problem-solving skills (Zheng et al., 2018). With the aid of these technologies, operators may overcome obstacles more successfully, assign tasks more efficiently, and collaborate with robots in a more secure and flexible manner. Adopting these technologies is essential to improving productivity and accomplishing shared objectives in a human-robot collaborative environment that is continuously changing.

3.4. Reasoning

According to the authors, the cognitive ability to draw logical conclusions, make deductions, and use critical thinking to solve problems and make informed judgments can refer to reasoning in collaborative environments. It is a fundamental cognitive ability that is essential for maximizing the number of collaboration-related factors, including task distribution, job execution, communication, safety and ergonomics, adaptability and versatility, and overall productivity.

Human operators have easy access to a huge database of knowledge, data, and resources through cloud-based systems. By enabling operators to examine previous data, trends, and patterns and make more educated decisions about task allocation and execution, this abundance of knowledge promotes better reasoning (Erasmus et al., 2018).

By providing a secure and monitored environment in which to rehearse difficult scenarios, simulation technology contributes to improving the deductive reasoning of human operators. Operators can improve their thinking abilities and earn significant experience by repeatedly simulating a variety of collaborative tasks with robots (Bilberg & Malik, 2019).

Additionally, when used in conjunction with robots, AI can considerably improve human cognition. Operators can come to logical conclusions and make data-driven decisions regarding task distribution, communication, and adaptivity because of AI-powered systems' ability to process enormous amounts of data and spot patterns (Liu et al., 2019).

Human operators can use insights from large data sets to strengthen their reasoning skills by incorporating big data analytics (Zhong et al., 2017). By examining performance indicators and trends, operators can work with robots to better allocate tasks, expedite job execution, and increase overall productivity.

These technologies enable human operators to improve their deductive reasoning skills and achieve more effective robot collaboration. While simulation and AI offer invaluable knowledge and assistance in forming logical conclusions during difficult jobs, access to real-time and historical data promotes the ability to make informed decisions. Big data analytics provides crucial information to optimize task distribution, ensuring flexibility and adaptation in collaborative contexts.

3.5. Language

In the authors' view, the term "language" in HRC scenarios refers to the cognitive ability to comprehend, produce, and use verbal and written communication to communicate thoughts, ideas, and emotions. For seamless interaction and cooperation between human operators and robots in a variety of joint tasks, effective language skills are essential. Language proficiency can be significantly enhanced through the use of VR in HRC. VR enables operators to practice communicating with virtual robots in a risk-free environment by creating immersive and interactive scenarios. Through repetition, language skills are improved, and job performance and work distribution are executed more effectively (Green et al., 2008).

AI-driven solutions for language understanding and processing can also greatly improve communication between humans and robots. Robots can more effectively understand human instructions thanks to sophisticated natural language processing (NLP) techniques, promoting easier communication between human operators and robots (Huang et al., 2021). As a result, human operators can improve their language abilities and work with robots more successfully. VR provides a dynamic environment for practicing communication scenarios, promoting more precise instructions and improved comprehension between humans and robots. Robots are now more accurately able to understand and respond to human language thanks to AI-powered language processing, which also ensures efficient task distribution and execution.

3.6. Social Cognition

According to the authors social cognition can be defined as the cognitive ability to comprehend and participate in social interactions with other human operators and robots in the context of HRC. It entails observing social cues, deciphering emotions, and expressing oneself effectively in a collaborative setting. Positive social connections between human operators and robots are fostered in a workplace that is inclusive and well-designed. In order to foster a supportive environment where operators can interact with robots more successfully during work allocation, job execution, and general communication, it is important to create locations that encourage open communication and collaboration. Moreover, by recognizing and responding to the emotions and well-being of human operators, the integration of environmental sensors into the collaborative workspace might enhance social cognition. In order to improve safety, ergonomics, and overall productivity, robots can adjust their interactions in response to stress levels or weariness (Kamble et al., 2018).

On the other hand, AI has a significant impact on HRC's social cognition (Demir et al., 2019). Modern AI-powered systems are able to capture human emotions, which enables robots to react appropriately and empathetically. During work allocation, job execution, and adaptivity, this encourages more effective communication and collaboration between human operators and robots.

In conclusion, human operators can improve their social cognition and work with robots more successfully. While environmental sensors enable robots to change their behavior based on operators' emotional states, AI-powered social cognition improves robots' comprehension of and responsiveness to the needs of human operators, resulting in more efficient work distribution, execution, and overall productivity.

4. Cognitive Capabilities enhancing Human-Robot Collaboration: a Digital Twin scenario

Industrial operations could be revolutionized by the incorporation of technology that improves cognitive capacities. In this context, the digital twin emerges as a compelling choice to harness the power of these technologies (Tao et al., 2019). The digital twin presents a flexible and scalable framework for smoothly integrating cognitive skills by producing a virtual counterpart of actual physical systems and procedures. As you can see in Figure 3 the Digital Twin is allocated the center of the system and supports the Human Operator by gathering and analyzing data through AI-enhanced simulation other than providing AR/VR applications to visualize information and details useful for the production. Solutions are proposed to the Human Operator that is able to evaluate different scenarios. This enables organizations to leverage advanced analytics, AI, simulation, VR, and other technologies to enhance decision-making, optimize operations, and drive HRC to new heights.

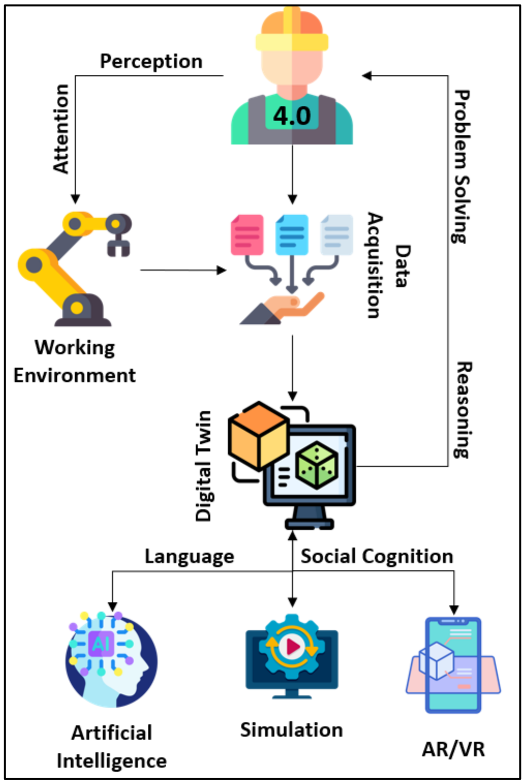

Figure 3. Digital Twin high-level architecture for Operator 4.0

Integrating cognitive capabilities through Industry 4.0 domain technologies to the digital twin enhances operational effectiveness and decision-making. The digital twin can evaluate enormous volumes of data in real-time using powerful analytics and machine learning algorithms, allowing operators to make deft judgments based on precise insights (problem solving and reasoning). The collaborative environment benefits from increased productivity and more efficient operations as a result of these decision-making process optimizations. Additionally, thanks to cognitive technology, the digital twin can simulate and forecast results, allowing operators to test various scenarios in terms of task allocation and job execution and optimize processes before putting them into practice in the real world. With this simulation capacity, risks are reduced, downtime is cut, and overall performance is improved. Operators can spot possible problems or bottlenecks, enabling proactive changes and upgrades that ultimately lead to higher output and lower costs. The digital twin's capability to continuously learn and adapt is another important benefit. Moreover, obtaining important data from the working environment and sensors enables the system to adapt environmental aspects such as ambient lighting and production parameters to enhance attention and perception for the human operator. The digital twin can learn from ongoing operations by utilizing AI and machine learning, thus enabling more effective communication (language) between humans and robots and also improving the social cognition of the system in general. The digital twin may improve its performance, identify anomalies, and make intelligent suggestions for solutions to problems in real-time thanks to these adaptive capabilities. Such adaptability improves human operator and robot collaboration since they can work together in a more responsive and effective way. In addition, the digital twin's use of big data analytics offers insightful information about operational patterns, trends, and correlations. Operators can better grasp the collaborative setting, spot areas for improvement, and adjust operations as necessary. By empowering operators to make data-informed decisions, this data-driven methodology enhances teamwork and produces better outcomes. Integrating cognitive capabilities into the digital twin also enhances safety and risk management. Operators can evaluate safety procedures and spot potential risks by using simulation technology before putting them into practice in the real world. This proactive method reduces hazards, enhances security protocols, and offers a safe working environment for HRC.

5. Conclusions

The concept of the Smart Operator, or Operator 4.0, signifies a transformative era in industrial settings where human workers leverage advanced technologies to enhance productivity, efficiency, and collaboration. In this paper, we investigated the integration of cognitive capabilities and Industry 4.0 technologies in HRC. Moreover, we proposed the integration of such technologies in a scenario of a Digital Twin simulation model. The integration of cognitive capabilities in the digital twin offers significant advantages for HRC. Improved decision-making, operational efficiency, simulation capabilities, continuous learning and adaptation, data-driven insights, and enhanced safety measures are among the key benefits. By harnessing the potential of these technologies, organizations can unlock the full potential of collaborative operations and drive innovation in various industrial domains. The future goal of this preliminary study is to integrate these technologies step by step within a real-time simulation model in order to improve the cognitive capabilities of the human operator in collaborative contexts. The first step will be to create within a controlled environment a collaborative context in which the human operator and the robot are expected to perform a set of tasks whose roles are interchangeable. To this end, the idea is to create a continuous data flow to use AI and simulation algorithms in order to define the allocation of jobs between the human operator and the robot based on specific ergonomic and production KPIs.

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