Challenges and Conceptual Framework to Develop Heavy-Load Manipulators for Smart Factories

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Abstract - Industry 4.0 has been one of the emerging topics in recent years, covering a wide range of concepts and applications as well as political, economic and technological views. Manufacturing is becoming smarter and smarter at all levels, moving toward the concept of Smart Factory (SF), based on the advancements of digital transformation technologies, including Artificial Intelligence (AI) and bigdata analytics, and abilities to learn, configure and execute with cognitive intelligence of smart machines and automation systems. However, the SF adoption in practice, especially in Small and Medium-sized Enterprises (SMEs), is still in the early stage. In addition, there are growing demands of product personalisation, mass-customisation and diversification. Therefore, the involvement of humans is still importantly required in many production processes in SF models, where smart machines, smart manipulators, collaborative robots and Automated guided vehicles (AGVs) are required to co-work with humans, leading to an important concern of safety, reliability, productivity and quality of smart manufacturing systems. In this paper, challenges and a proposed conceptual framework to develop smart heavy-load manipulators are presented, with the focus on the cost-effectiveness and applicability in industrial practices of SF for SMEs.

Keywords: Smart factory, industry 4.0, manipulators, cobots, automated guided vehicles.

1. Introduction

The Fourth Industrial Revolution or Industry 4.0 has been one of the emerging topics in recent years, covering a wide range of concepts and scope of applications as well as political, economic and technological views [1, 2], in which research and technology development on smart manufacturing plays an important role, with the following related core technologies and keywords: artificial intelligence (AI), big data analytics, internet of things (IoT), autonomous robots, additive manufacturing, cloud computing, cybersecurity, virtual reality and augmented reality, digital twin, optimization and simulation. Although many countries have priority plans to move toward ser-vice-oriented economies, with the focus on the financial and knowledge-based ser-vice industry, the manufacturing industry is still important for the growth of many national economies. The manufacturing industry accounts for almost 17% of the global GDP in 2019; and for the middle and upper middle-income countries, the value added by the manufacturing industry is from 15% to 25% GDP [5]. Smart manufacturing is a broad concept of manufacturing that enable all information and data across the entire manufacturing processes, supply chain and product life cycle to be smartly and optimally collected, analysed, managed and con-trolled, with a rapid and dynamic response to new demands and changes [3, 9]. In this way, manufacturing is becoming smarter and smarter at all levels based on these core advancements, especially digital transformation technologies, AI and bigdata analytics, and abilities to learn, configure and execute with cognitive intelligence, leading to the concept of Smart Factory (SF) [2- 4, 6, 10]. Figure 1 presents the concept and model of smart manufacturing and its smart elements with SF as the central point. In SF, humans and production processes are supported by the presence of intelligent, computer-based systems, to ensure a seamless, continuous flow of production for increased performance and quality [6], with a high level of autonomous cooperation of machines which are equipped with smart sensors and devices for simultaneous data collection, processing and analysis to smartly control manufacturing processes and automation systems. Theoretically, within the scope of smart manufacturing and Industry 4.0, there is a high level of automations and intelligence such as self-perception and self-decision-making, with involvement of smart engineering systems such as CNC (Computer Numerical Control) machines, industrial robots, collaborative robots (cobots) and Automated guided vehicles (AGVs) [8]; and the involvement of human workforce (workers) in production processes in SF is absent or minimum. However, the SF adoption in practice, especially in Small and Medium-sized Enter-prises (SMEs), is still in the early stage [4]. The involvement of human workforce is still importantly required in many production processes in SF, especially where smart machines and cobots [7] are required to co-work with humans (co-workers), including cases of handling and lifting heavy loads as well as complex assembly operations, in order to meet the growing demands of product personalisation, mass-customisation and diversification, as well as to meet special requirements with the on-demand manufacturing [23] and service-oriented manufacturing strategy.

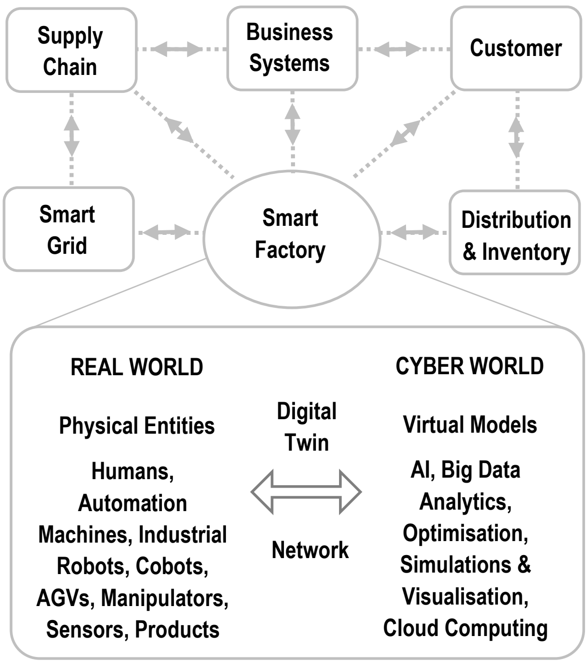

Figure 1: Elements of Smart Manufacturing with SF as the central point

When there are close interactions between the machines and humans in the manufacturing shop floor and warehouse, there is an important concern safety, reliability, productivity and quality of smart manufacturing systems. Figure 2 presents a sample SF layout with involvement of the following ones in the manufacturing shop floor: humans, machines, conveyors, industrial robots, cobots, AGVs, manipulators, sensors and products in the manufacturing processes. There are 4 main manufacturing pro-cesses P1 to P4, 2 traditional AGVs, 2 AGVs with cobots, 2 cobot cells, 2 industrial robot cells, and 1 heavy-load manipulator which flexibly move in the shop floor. Since there is a heavy-load manipulator manually controlled and operated by hu-mans (workers) in SF, the issues related to safety, reliability, productivity and quality of smart manufacturing systems need to be taken into account; because smart elements and systems in the SF shop floor such as cobots and AGVs are required to directly and indirectly co-work with humans.

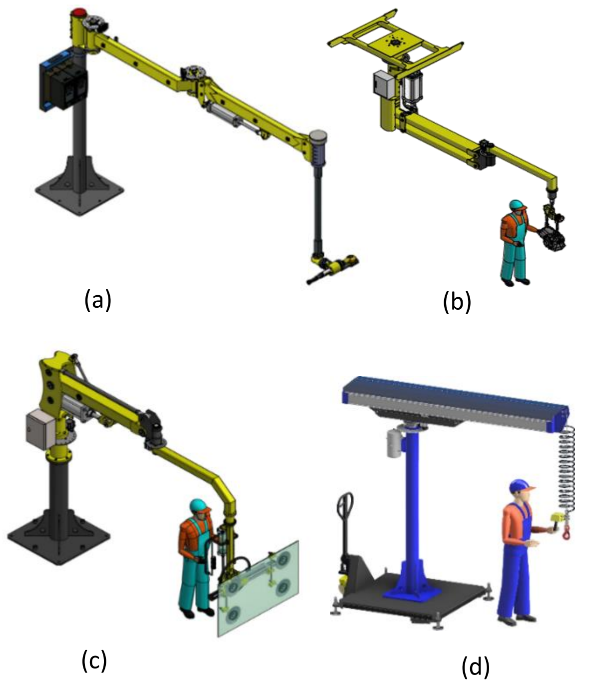

Figure 2: Different design of the traditional heavy-load manipulators. (a, b, c): Pneumatic manipulators. (d) An electric manipulator.

The presence of humans in the shop floor and warehouse also lead to the challenges and complexities in production planning and control in SF, especially simulations and optimisation tasks. In addition, safety issues for human workforces who operate and control the heavy-load manipulators need to be especially considered; and in this way, the safeguards and frameworks for design and development of smart heavy-load manipulators need to be systematically investigated, taking into account the constraints from related elements in SF, including humans, CNC machines, conveyors, industrial robots, cobots, AGVs, sensors and parts or products. Finally, the collaborative workspace for key SF elements, especially AGVs, cobots and heavy-load manipulators, should also be carefully considered, to avoid the potential hazards and to minimise potential risks related to safety issues.

2. Challenges to Develop Smart Heavy-Load Manipulators for Smart Factories

There are different types of heavy-load manipulators with auto weight sense and auto balancing systems which allow manually handling and lifting the objects with different weights and sizes via a long joint equipped with multi-functional end effectors as shown in Figure 3. The heavy-load manipulators as a part of the logistic transport systems are used to support handling, lifting and moving the heavy objects in the manufacturing shop floor or warehouse. Basically, most of the traditional heavy-load manipulators are based on the pneumatic control and drives which are widely used in robotics and automation systems due to their high reliability and cost-effectiveness. There are also heavy-load manipulators which are based on electric control and drives (Fig.1 (b)), with a lower carrying capacities compared to the pneumatic ones. The main advantages of the traditional heavy-load manipulators include: (1) easily and conveniently handling and lifting the heavy loads with carrying capacities of up to 1500 kg, mostly in the range of 50 kg - 300 kg, (2) accurate positioning and self-balancing capability; and (3) the work envelope or workspace is big-ger compared to industrial robot arms and cobots.

With the advancement of robotic technologies, the heavy-load cobots have been recently developed for commercialisation with many outstanding features compared to traditional manipulators and industrial robots. The main advantages of the cobots compared to the traditional manipulator and industrial robots include (1) it is safer when working and interacting closely to humans, (2) The number of degrees of freedom and flexibility in handling and lifting are normally higher compared to the traditional manipulators, (3) no requirement of safeguards such as required for industrial robots, the fences or other obstacles can be removed to create a barrier-free floor; (4) cobots and human can co-work with each other to assist particular skills and tasks, and cobots support humans as they perform manual operations by optimising the work process [12, 13]; (5) cobots are equipped with easy control and handling systems with learning capabilities, and the new tasks for a cobot can be taught quickly; and (4) potential applications in SF and Industry 4.0 via smart as well as robust and self-control capabilities. However, the carrying capacities of cobots are low compared to the heavy-load manipulators. Figure 4 presents the highest payload cobots commercially available on the market, including: (1) the cobot CR-35iA made by FANUC Robotics, with the maximum payload of 35 kg [11], and (2) the cobot AURA made by Comau with the maximum payload of 170 kg [12].

With the outstanding capabilities and smart features, when cobots are introduced to SF such as shown in Fig.2, there should be no problem and big issues related to safety and potential hazard to co-workers. However, since the carrying capacities of the cobots and AGVs are low, the use of heavy-load manipulators is still necessary in SF, especially the one for SMEs. In addition, as mentioned in Section1, there are growing demands of product personalisation, mass-customisation and diversification. There-fore, the involvement of human workforce is still importantly required in many pro-duction processes in SF in SMEs, not only for co-working with cobots, but also for handling and lifting heavy objects with heavy-load manipulators, as well as working on complex assembly operations, especially to meet special requirements with on-demand manufacturing and service-oriented manufacturing strategy.

(a) (b)

Figure 4: Commercially available collaborative robots of heavy payloads. (a) The cobot CR-35iA made by FANUC Robotics, with the maximum payload of 35 kg [11], and (b) the cobot AURA made by Comau with the maximum payload of 170 kg [12].

The human workforces in SF should be protected from all hazards during co-working on the shared tasks with cobots and operations performed by robots, AGVs and automation systems such as CNC machines and conveyors. All safeguarding systems should be smartly activated and controlled, especially when human workforces who operate and control heavy-load manipulators are within the safeguarded area of cobots, AGVs, robot cells and automation systems in SF. In this way, in order to de-sign and develop as well as to optimally use the heavy-load manipulators in SF, it is necessary to identify potential challenges and issues that need to be taken into ac-count, especially the ones related to safety, reliability, productivity and quality of smart manufacturing systems.

2.1 Challenge 01: Collision prevention and safety issues when operating and handling the heavy-load manipulators.

Besides the general technical requirements related to the safety and reliability, there are challenges related to the safety issues due to the movements of humans and automation systems in the manufacturing shop floor or warehouse of SF. The networks of flexible, modular and scalable automation systems in SF such as AGVs and cobots are required to operate in safe and collaborative way with humans. Therefore, there should be solutions to enhance the capability of collision avoidance and detections in order to avoid the potential hazards to humans and risks related to safety issues. It is noted that although AGVs are programmed and controlled to search the idle path and avoid collisions, there are still potential risks and hazards to humans related to the specific tasks of the robot arms of AGVs and objects that AGVs carry in the manufacturing shop floor or warehouse. In addition, in order to maintain the load balance between AGVs of different zones, the collision prevention strategies for AGVs are not only based on the fixed guide path layout strategies and fixed zone strategies [14], scheduling for AGVs and collision prevention for AGVs and human workforces who directly operate and control heavy-load manipulators in the manufacturing shop floor and warehouse become more complex.

Figure 5: Different design of the traditional heavy-load manipulators. (a, b, c): Pneumatic manipulators. (d) An electric manipulator.

Figure 5 presents the innovative solutions to develop the cobot via the use of the "skin" system with integrated proximity sensors which covers a robot and allow it to detect the presence of nearby objects without any physical contact [12, 13]. In this way, the robot can operate in safe and collaborative way with humans without sacrificing payload or performance, with the maximum payload of 170 kg [12], com-pared to the currently common payload from 10 kg to 35kg of cobots. The similar innovations may be applied for the case of heavy-load manipulators, to enable the ability of automatic avoidance detections in a safe, collaborative and smart ways.

In the case it is required to design collaborative workspaces, access and clearance to mitigate unintended contact that is potentially hazardous to the human co-worker when performing cooperative or collaborative tasks with cobots, the ISO 15066 and ISO 31000 standards with active and passive design safeguards [18] need to be taken into account, including the tasks of working on hazard analysis and risk assessment.

2.2 Challenge 02: Real-time position tracking and localisation of humans, heavy-load manipulators and automation systems in the manufacturing shop floor and warehouse.

In order to optimally and smartly plan for collision prevention and safety issues when operating and handling the heavy-load manipulators in the manufacturing shop floor or warehouse of SF, the real-time accurate and dynamic position-tracking and localisation of heavy-load manipulators and automation systems is important, especially when the movement of heavy-load manipulators as well as the weight and size of the objects (parts, functional units, products) are frequently changed. The ability to track position with respect to the movements of the heavy-load manipulators, humans, cobots and AGVs need to be taken into account when designing smart heavy-load manipulators for applications in SF.

This becomes more important when AGVs are self-organised and allowed to use an entire space of the manufacturing shop floor and warehouse, they are not based on the fixed guide path layout strategies and fixed zone strategies to complete the transportation tasks along the established paths via instructions received from the control centre [14, 15].

In SF, a group of AGVs and cobots that is normally tasked to transport without collisions to predefined locations, or and co-work safely with humans and other automation systems. There are different ways for position-tracking and localisation of AGVs, including (i) vision based methods with the use of the camera installed on the top of the warehouse to capture the global image that is used for position tracking [15], and (ii) the use of range sensors such as 3D LIDAR, commonly used in in autonomous vehicle technology [16, 17]. However, when the heavy-load manipulators which are manually operated and handled by human workforce are present, the level of automations and intelligence such as self-perception and self-decision-making is affected. In addition, if movement paths as well as the weight and size of the objects to be handled are frequently changed, this leads to the changes of the combined work envelope or workspace of the heavy-load manipulator, human and objects. Therefore, the position-tracking and localisation problems become more and more complex when there is a presence of humans and heavy-load manipulators in the manufacturing shop floor and warehouse.

2.3 Challenge 03: Motion and task coordination problems between humans, manipulators, cobots, AGVs and other automation systems.

Ideally, the involvement of human workforce in production processes in SF is absent or minimum [1-3]. However, the SF and Industry 4.0 adoption in practice, especially in SMEs, is still in the early stage [4]. According to survey done by the Korea Federation of Small Business, only 40% of Small and Medium-sized Enterprises (SMEs) understood the concepts of a smart factory, and only 6.3% of SMEs had plans to prepare for a systematic response [4]. In addition, there are challenges related to the lack of skilled workforce and financial resources, leading to a varying degree of adoption of the SF and Industry 4.0 principles in industrial practices. As mentioned in the previous sections, there are growing demands of product personalisation, mass-customisation and diversification. Therefore, the presence of human workforces in the manufacturing shop floor and warehouse is still necessary and important. Especially the heavy-load manipulators are directly controlled and operated by human workforces as a part of the logistic transport systems to support lifting and moving the heavy objects.

In line with Challenge 01 and Challenge 02, besides it is necessary to take into ac-count the issues related to collision prevention and safety as well as the position-tracking and localisation, the challenges and issues related to motion and task coordination between humans, heavy-load manipulators, AGVs, cobots, industrial robots and other automation systems become complex. This is more complex when human workforces and heavy-load manipulators are necessarily required to directly interact with AGVs, cobots, industrial robots and CNC machines in the production processes.

2.4 Challenge 04: Cost-effective solutions, adoptions and applications in practice of SF and Industry 4.0 models

With rapid technology advancements and well-recognised impacts of digital trans-formation technologies, there have been a lot of efforts in recent years at the global and national scope to develop technology eco-systems moving toward Industry 4.0 , including Germany's High-Tech Strategy 2020 Action Plan for Industry 4.0 in 2013, China's National Strategic Plan "Made in China 2025" in 2014, and EU's European Factories of the Future 2020 roadmap and Factory 4.0 in 2013 [4, 20]. As mentioned in Section1, the service-oriented industries play an essential role in increasing the add-ed value to the economy, especially the financial and knowledge-based service industry, the manufacturing industry is still important for in the growth of many national economies [5].

However, the manufacturing industry is more vulnerable compared to the service one due to the constraints related to human workforces and manufacturing resources as well as the economic fluctuations and recessions. In addition, the manufacturing industry is heavily affected by the pandemic such as Covid-19; and it was estimated by the United Nations Conference on Trade and Development (UNCTAD) that the COVID-19 pandemic could cause global FDI to shrink by 5 to 15%, due to the downfall in the manufacturing sector coupled with factory shutdown [21]. Therefore, it is important and necessary to take into account the cost-effective and responsive solutions as well as the impacts and applications in practices when designing and developing technologies for applications in SF.

Since the SF applications in practice are still in the early stage. Meanwhile, there have been a lot of proposed SF conceptualisations with different degree of automation and absence of human workforce [1-4, 22]. Therefore, there are challenges to fully develop and apply in industrial practices the ideal SF models [1-3] in the next 5 to 10 years. It is necessary to develop the cost-effective SF models that are easy to under-stand with a high level of applicability in practice and adoptability for SMEs, including the cost-effective solutions for design and development of the key elements of SF, including smart heavy-load manipulators, AGVs and cobots. This is more important for SMEs when implementing plans toward Smart Manufacturing and Indus-try 4.0, because the lack of skilled workforce and financial resources, standardization problems and cybersecurity issues may be particular problems [22].

2.5 Challenge 05: Applications of LEAN principles, production planning and scheduling, and simulations of real-world physical behaviour and characteristics of SF.

Lean manufacturing principles have been widely adopted to continuously improve the manufacturing operations, with the focus on elimination of wastes and activities which add no value to the manufacturing process. In the SF shop floor, work-in-progress (WIP), machines and other physical resources are endowed with intelligence such as self-perception and self-decision-making, and it is expected that the task of production planning and scheduling becomes autonomous and it is done via autonomous communication between the WIP and the machines [24]. Through the digital twin system, especially simulations real-world physical behaviour and characteristics of SF, the interconnected networks of moving elements such as parts, products, cobots, AGVs, humans, heavy-load manipulators in a shop floor and warehouse can be optimized. This leads to opportunities to apply LEAN principles to improve a performance of SF via powerful simulation tools, as well as how to optimally integrate smart elements and new automation systems in the manufacturing shop floor and warehouse, especially the smart heavy-load manipulators, cobots and AGVs.

As addressed in the previous sections, in order to meet the growing personalised product demands, product diversification and mass-customisation, there are requirements to smartly and optimally integrate automated and semi-automated systems into production lines to cope with higher degrees of variety. There is also a presence of human workforces directly involving in operations of manipulators and collaborative tasks with automation systems such as cobots, AGVs, CNC machines and industrial robots. This leads to challenges related to horizontal and vertical system integration as well as simulations and data analysis for autonomous production planning, scheduling and control, especially to make the SF shop floor become smart and to enhance the capability of the human-like self-X intelligence of the SF elements such as self-perception, self-learning, self-organization, self-configuration, self-decision-making, self-control [24, 25]. In this way, the role of data driven intelligence and AI in smart manufacturing and how deep-learning [26] is applied in collaborative working spaces, especially simulations and optimisation of the work flows and collaborative tasks, need to be taken into account when working on designing and developing smart heavy-load manipulators.

3. Conceptual Framework to Cost-Effectively Develop Smart Heavy-Load Manipulators for Smart Factories

A conceptual framework to cost-effectively develop smart heavy-load manipulators for smart factories is proposed and presented in Fig.6, taking into account the identified challenges presented in Section 2 and latest developments of SF. This framework is aimed at cost-effective solutions in design and development as well as systematic integrations of smart heavy-load manipulators in SF, with the focus on the adoptability of SF and Industry 4.0 in practice for SMEs.

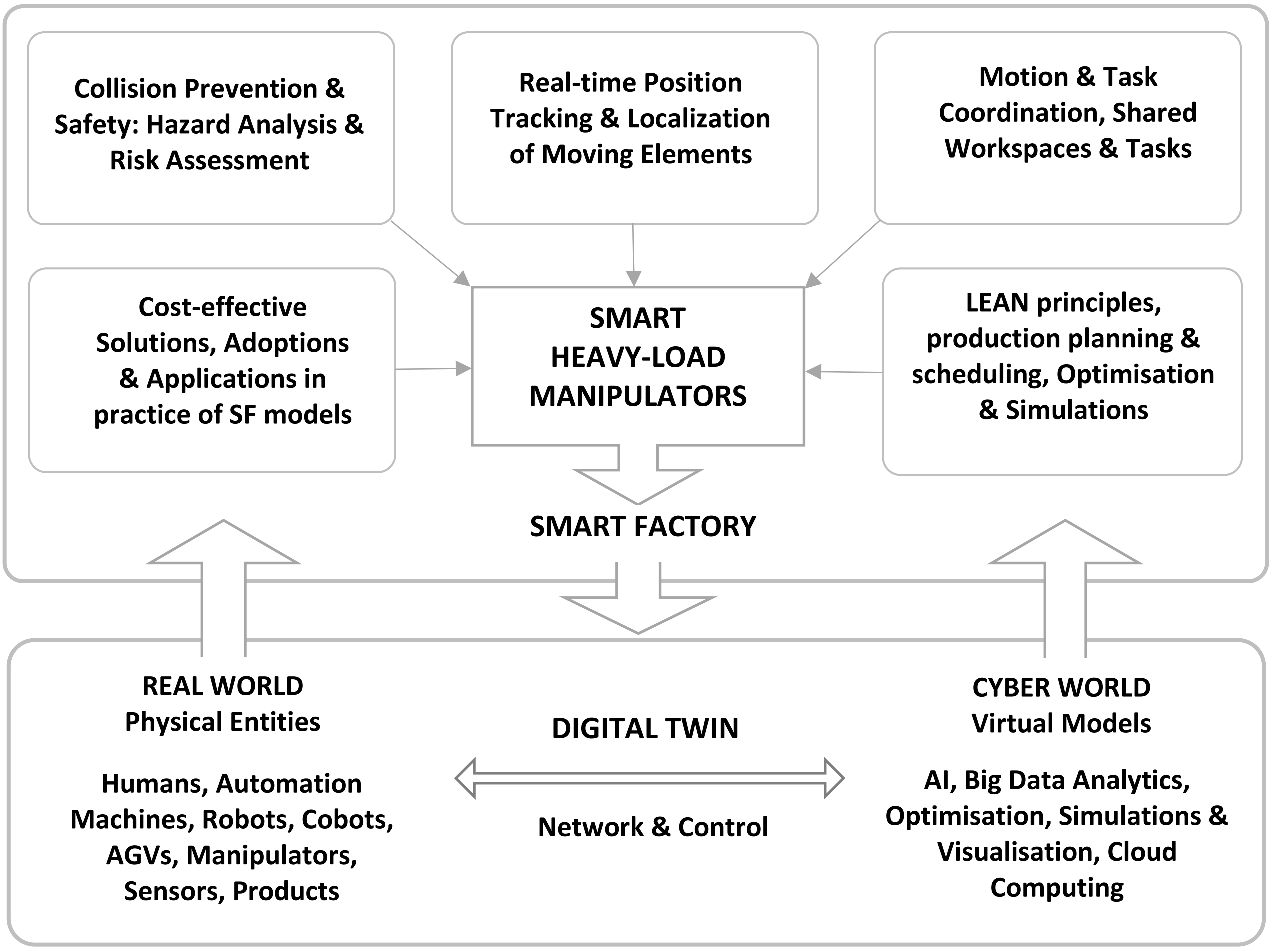

Figure 5: A conceptual framework to cost-effectively develop smart heavy-load manipulators for smart factories, taking into account the applicability in industrial practices of SF for SMEs.

In the manufacturing shop floor and warehouse of SF, the AGVs and cobots share the workspace and work collaboratively with human co-workers, and there is a presence of smart heavy-load manipulators which are manually operated and directly controlled by human workers. Therefore, first of all, the collision prevention and safe-ty as well as hazard analysis and risk assessment need to be well-addressed.

In addition, in order to obtain the real-time optimal control of the smart elements in the manufacturing shop floor and warehouse such as AGVs, cobots, industrial robots, CNC machines, and especially the heavy-load manipulators, the following issues and problems need to be considered: (i) real-time position tracking and localisation of moving elements, and (ii) motion and task coordination, shared work-spaces and tasks. Finally, it is necessary to take into account the issues and problems related to investment and applicability in practice, as well as continuously improving the manufacturing operations, and elimination of wastes and activities which add no value to the manufacturing process: (i) cost-effective solutions, adoptions and applications in practice of SF models; and (ii) applications of LEAN principles, production planning and scheduling, optimisation and simulations.

Since it is required to work in SF, the heavy-load manipulators need to be smartly controlled and operated, and the latest development of the enabling technologies for Industry 4.0 should also be referred during the design and development process, including: Internet of Things (IoT), AI, Big Data Analytics, Optimisation, Simulations and Visualization, and Cloud Computing.

4 Summary and Conclusion

In this paper, challenges and a proposed conceptual framework to develop heavy-load manipulators for smart factories are presented, with the focus on the cost-effectiveness and applicability in industrial practices of SF for SMEs.

In order to meet the growing demands of product personalisation, mass-customisation and diversification, the involvement of human workforce is still importantly required in many production processes in SF, in which cobots and AGVs with cobots co-work with humans in the shared workspace, especially in cases of heavy-load handling as well as complex assembly operations. This leads to an important concern of safety as well as reliability, productivity and quality of smart manufacturing systems, related to potential unwanted contacts and close interactions between human, cobots, AGVs, CNC machines and automation systems. Therefore, the safety systems for collision avoidance and/or contact mitigation as well as safety measures must be adequately implemented when working on design and development of the manufacturing workcell as well as the smart elements for SF. More attentions should be taken into account for the case of the heavy-load manipulators, because the human workforce is required to directly control and manually operate in the manufacturing shop floor and warehouse. Moreover, the smart elements in SF such as cobots and AGVs are endowed with intelligence such as self-perception and self-decision-making, and AGVs can be self-organised and allowed to use an entire space of the manufacturing shop floor and warehouse. Hence, it is not only required to protect the human workforce and to avoid the unexpected and unwanted collisions, the issues and challenges related to maintaining the optimal performance of a manufacturing system need also to be taken into account.

Besides the technical requirements such as accurate positioning and self-balancing capability when handling and lifting the heavy payloads, the smart heavy-load manipulators need to be designed and integrated with smart sensors and controllers, to obtain the relevant intelligence such as self-perception and self-decision-making when it is used to co-work with cobots, AGVs, CNC machines and automation systems in SF.

The identified challenges and proposed conceptual framework can also be useful when working on hazard analysis and risk assessment of SF, as well as designing and selecting smart elements for SF such as AGVs, cobots, industrial robots [26-28], robot cells and automation systems.

Acknowledgement

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