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Towards automatic configuration and programming of a manufacturing cell

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ABSTRACT

Manufacturing industries are moving from mass production towards customized production, aiming for high-quality products with innovative technologies, low prices, and high reliability. A reconfigurable manufacturing system (RMS) is an attractive approach to facilitate the movement toward such flexible manufacturing systems. However, reconfiguration and programming of RMS are time-consuming and labor-intensive. Industry 4.0 technologies (such as robotics, digital twin technology, and IoT solutions) decrease human interaction in the preparation phase of a new production series. One challenge that industry 4.0 does not address is a flexible electrification of the system. The lack of electrical outlets limits the available space on the shop floor, and extensive cabling constrains the motion of humans and machines in the same area. This paper solves these challenges by proposing a highly flexible RMS system with advanced robotics, a digital twin programming interface, and a wireless power transfer (WPT) solution. Experimental results, through simulations and verification by laboratory experiments, show great potential in the reduction of human interaction and time to set up a new manufacturing line.

1. Introduction

Globalization has put intense competition between manufacturing companies to produce high-quality products with innovative technologies, low prices, and high reliability. The increasing competition between manufacturers motivates them to move away from mass production towards mass customization and personalized production [1]. Competitors need to adapt and change depending on the market changes, product changes, system failures [2], or global health crises [3].

We can categorize manufacturing systems into three main categories; dedicated manufacturing system (DMS), flexible manufacturing system (FMS), and reconfigurable manufacturing system (RMS). The DMS focuses on high volume and low variety production, while the FMS focuses on low volume and wide variety. In contrast, RMS combines the advantages of both systems to produce with high volume and wide variety. Koren et al. [4] defined RMS as a manufacturing system that can adjust its resources. Thus, RMS is an attractive approach to solve the previously mentioned challenges.

Reconfiguration of RMS can be time consuming. Kim et al. [5] found that in their RMS, the most time-consuming part is the physical rearrangement of the modules and reconfiguring of the system. The system also needs physical labor to rearrange or change the modules in the manufacturing system. As the RMS is scalable, increasing the size of the system results in scaling up the RMS challenges. In other words, with the increasing number of modules of the RMS, the reconfigurable time increases, and the required labor to reconfigure the system will also increase. Moreover, increasing the system scalability adds more demand on the computation, communication, and system complexity [6].

Industry 4.0 is the next technological revolution that focuses on increasing connectivity, automation, and intelligence in manufacturing [7]. The technologies in industry 4.0 are advanced robotics, the internet of things (IoT), cyber-physical systems (CPS), cloud computing, augmented reality, additive manufacturing, and big data are essential for the success of RMS in the future [8]. Industry 4.0 technologies can improve and automate the rearrangement of RMS. However, Bortolini et al. [9], revealed that there is still a lack of research on industry 4.0 integration in RMS. Maganha et al. [10] mentioned that using industry 4.0 technologies must be considered when designing the layout of the system and that the technologies can allow for smart layout design of the RMS.

Morgan et al. [11] suggested that there is a need to retrofit current

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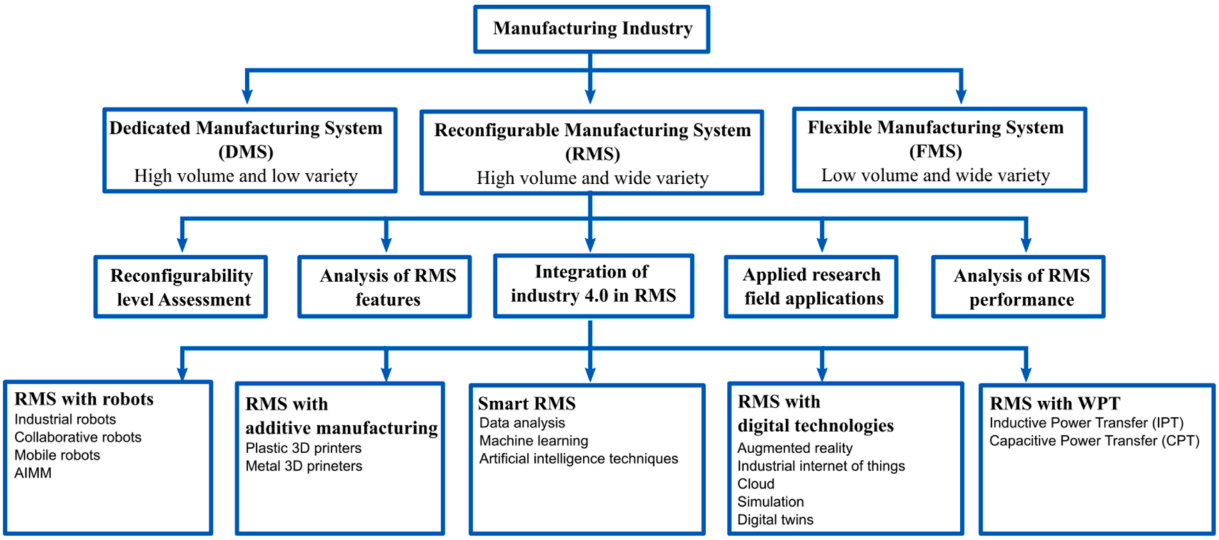

Fig. 1. The research direction for RMS based on Bortolini schematic [9], with a focus on industry 4.0 integration to RMS.

manufacturing equipment with the new technologies. Thus, we can retrofit old robots with new controllers, IoT functionality, and adaptable control systems. Using advanced robotics, IoT, and digital twins, we can control and automate the reconfiguration of RMS. The robots can rearrange the modules in such a system, while the IoT offers wireless control and communication.

Although industry 4.0 tackles most RMS problems, there is still a challenge with electrification. Systems need labor to connect all parts to power, and it is time-consuming. Besides, the conventional electrification uses cables that require large areas, which limits the flexibility of the systems. Therefore, there is a need for more flexible methods to power RMS without human intervention. Wireless power transfer (WPT) can energize the system autonomously and has the potential to address the challenges in the conventional conductive charging approach, including long charging time, wear and tear of the contractors and plugs, and hazard of the electric shock.

To the authors' knowledge, there is no publications which use mobile robot to rearrange the machines in the manufacturing cells. Arnarson et al. [12] used one mobile robot to move multiple robot arms. We can expand this conceptual idea by moving different manufacturing machines using a mobile robot. In addition, there is no investigation of WPT for manufacturing systems or consideration of WPT as an industry 4.0 technology. Industry 4.0 is a dynamic concept where various technologies are in industry 4.0 can and will change over time [7]. For instance, one of the main technologies in industry 4.0 is IoT which can connect devices wirelessly. WPT provides wireless electrification of systems, we can argue that WPT is a new and emerging industry 4.0 technology that can allow manufacturing systems to become more flexible, modular, and automated.

Expanding Bortolini framework [9], we can categorize the research directions of industry 4.0 in RMS, as shown in Fig. 1. The first industry 4.0 technology is RMS with robots, including industrial robots, collaborative robots, mobile robots, and autonomous industrial mobile manipulators (AIMM) in RMS. RMS with additive manufacturing looks at implementing 3D printers into the system. RMS with digital technologies which embrace augmented reality, industrial internet of things (IIoT), cloud, simulation, and digital twins. Smart RMS encompass data analysis, machine learning, and other artificial intelligence techniques. Finally, RMS with WPT looks at flexible and autonomous electrification for manufacturing systems.

In this paper, we propose an autonomous RMS by integrating a mobile robot into RMS, to increase the reconfigurability of the system, decrease the setup and programming time, and enhance the system's flexibility. Besides, we investigate different WPT configurations that increase flexibility and autonomy, creating a highly flexible RMS. We can summarize the main contribution of the paper as follows: .

- Proposing a new RMS in which a mobile robot can reconfigure the system.
- Rearranging, and monitoring the proposed system using a digital twin solution.
- Proposing static and dynamic WPT as industry 4.0 technology for RMS.
- Retrofitting old manufacturing machines with industry 4.0 technology.
- Simulating and verifying through laboratory experiments and video presentations.

We organize the remainder of this paper as follows: Section 2 presents previous studies on RMS. Section 3 proposes the concept of a highly flexible mobile RMS with WPT. Section 4 describes a mobile RMS with a digital twin, a physical demonstration of the system. Then, we discuss the results in Section 5. Finally, we conclude and present our future works in Section 6.

2. Previous studies

Sanderson et al. [13] developed the Smart Manufacturing and Reconfigurable Technologies (SMART), which is an assembly system that can be set up with different configurations. The system is based on the HAS-200 system [14] and applies adaptive multi-agent control. There are other similar examples on smart RMS [15–18]. They used standardized platforms from the CP Factory. CP Factory is a universal modular manufacturing systems for research, training, and teaching, produced by FESTO [19]. The systems use platforms that can be rearranged based on the system's capacity and functionality.

In another study, Kim et al. [5] introduced a modular factory testbed. The system consists of 10 main workstations producing portable battery chargers, electric endodontic handpieces, and electric toothbrushes. The system uses a infrared communication system that automatically recognizes how the system is configured. However, all the previous systems (i.e., CP factory, HAS-200, and testbed) are only used for training, educational, and research purposes.

Adamietz et al. [20] presented a miniaturized RMS. The system uses a standardized container, in which it is possible to change the manufacturing modules inside the container. This system can have a

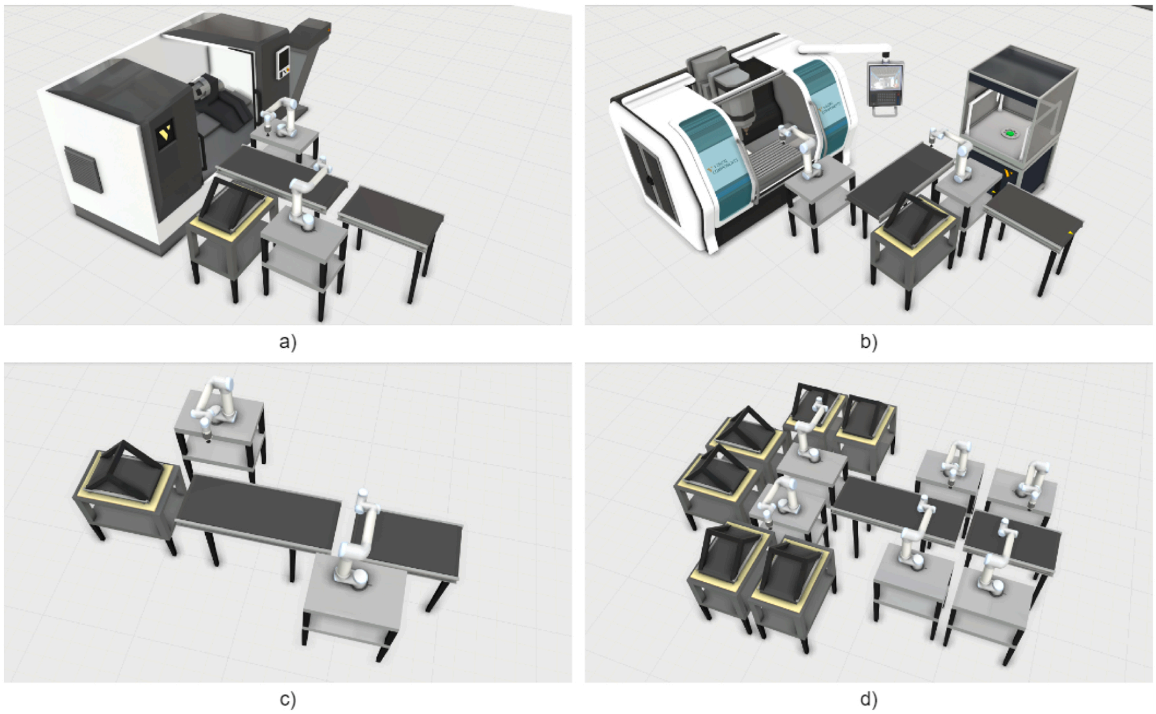

Fig. 2. Different examples of how the system can be configured (a, b) and scaled up and down (c, d): (a) The platforms are arranged around the turning center, (b) the platforms are arranged around a large 3D printer, (c) a small manufacturing system using the platforms, and (d) the previous manufacturing system is expanded with more platforms to increase production.

maximum of six small modules, three large modules, or a combination of big and smaller modules. The system reconfiguration takes less than 8 h using a forklift, where a human needs to move the parts between the machines.

Seok et al. [21] built a modular manufacturing system using the additive manufacturing concept. Their system consists of, 3D printers, post-processing, inspection, and packing modules. It uses a 3D printer as the main manufacturing process, and it is possible to achieve personalized production or mass customization. We can categorize the system as an RMS with digital technologies.

One approach that can save time and automate the RMS is the AIMM principle. Hongtai et al. [22] explained the concept of AIMM as a mobile robot combined with an industrial manipulator. The robots are easy to integrate and can carry out tasks at different workstations. The AIMM increases manufacturing flexibility and we can implement it into existing manufacturing systems [23]. Recently, Inoue et al. [24] proposed AIMM to be a key component of RMS. Andersen et al. [25] examined how to integrate an AIMM into a modular CP Factory.

Regardless of these previous studies, there is little attention to building and designing RMS for manufacturing industries. For instance, Singh et al. [26] revealed that there is inadequate research on the development of principles for reconfigurable machines. Moreover, Khanna et al. [27] found that the implementation of RMS into manufacturing systems is still a significant problem. In addition, there is a lack of studies that explain RMS in practices and how RMS can be adapted and used by companies [28].

The previous studies showed that the physical reconfiguration of the platforms is the most time-consuming, and they require labor to change and modify the layout. Morgan et al. [11] proposed smart reconfigurable machines that can change autonomously. In another study, Singh et al. [26] found that there is immense potential for further research on wireless sensor networks for automatic configuration, interoperability, and scalability.

WPT plays a crucial role in charging applications without human intervention, making it attractive for developing flexible and reliable RMS systems. It reduces the hazards of electrical shocks by plugin cables. It can also minimize the systems' maintenance by removing the plugs, cables, and contractors. WPT provides an attractive solution in different applications: IoT devices [29,30], lightning [31–33], heating [34], wind turbines and oil drilling tools [35], energy encryption [36], unmanned aerial and underwater vehicles [37–40,41], and transportation applications [42–44].

To summarize, we found there is less focus on industry 4.0 integration. Moreover, all the previously proposed systems suffer from setup, layout, and programming restrictions. In addition, systems are still highly dependent on humans for reconfiguration and powering the system. If we use advanced robotics, IoT, and digital twin to rearrange the system, this can improve the flexibility and reconfigurability of the system. At the same time, implementing WPT will make manufacturing systems more flexible, modular and automated and support the other industry 4.0 technologies.

3. Concept of a highly flexible system

3.1. RMS with robots

To integrate industry 4.0 in RMS, we can use the concept of AIMM to utilize robots in a flexible manner. Arnarson et al. [12] proposed an AIMM for RMS, where the AIMM is divided into two separate parts, one for the mobile robot and a second for a robot arm. The mobile robot and robot arm can work together or separately. With such a system, one mobile robot can move multiple platforms and increase the utilization of both the robot arm and the mobile robot. In this example, they created two robot platforms. Using the same principle, we can expand the idea by adding conveyors, 3D printers, or other manufacturing machines to the platforms instead of a robot arm.

A mobile robot can move and rearrange all system parts to manufacture a specific product. The mobile robot can also rearrange around large manufacturing machines (CNC, turning, and 3D printer) that are fixed and hard to move. This solution is scalable since adding new

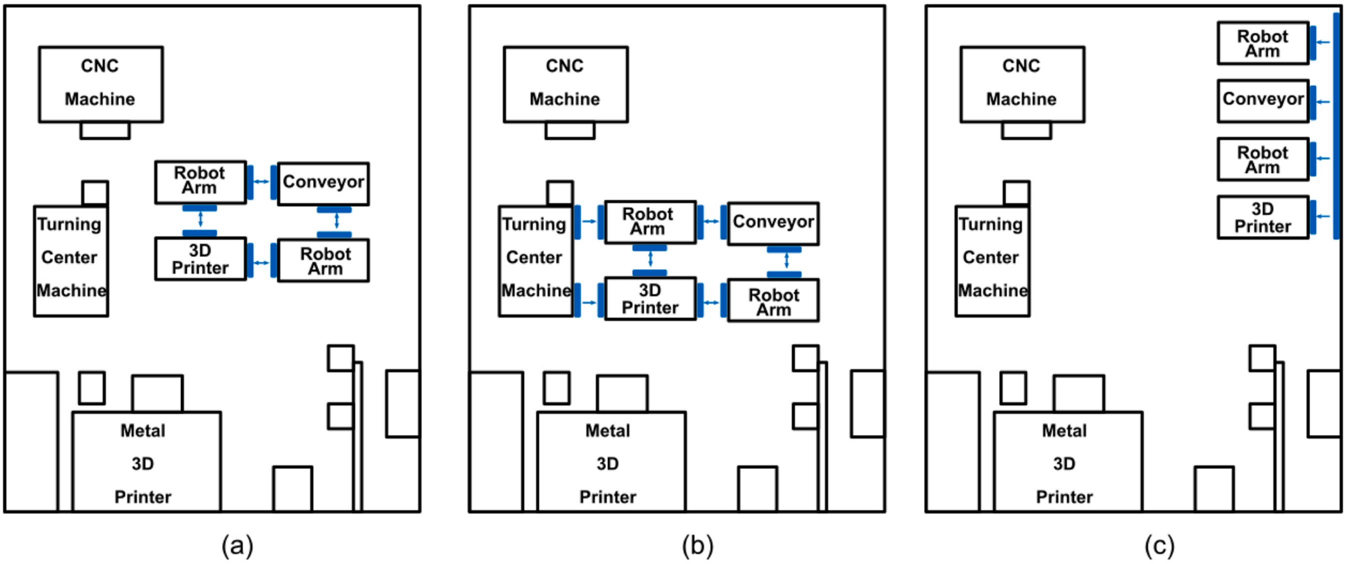

Fig. 3. A top-view of three different scenarios for static WPT: (a) the platforms charge each other through a mesh configuration. (b) the platforms charge each other through a mesh configuration while a big machine energizes the whole system. (c) the platforms charge from the main source while they are parking.

platforms to the system can increase the output and production capacity. Therefore, it is easy to downscale and upscale production based on demand. Fig. 2 shows how to configure the system with different scalable layouts. At the same time, we can also use collaborative robots in open environments where humans are working or industrial robots for tasks that require higher precision and accuracy.

3.2. 3D printing

Another emerging industry 4.0 technology is additive manufacturing, in which we can get an even more flexible and automated RMS. For instance, in the conventional manufacturing approach to produce a plastic box, we need to build a mold and other related manufacturing machines that are not flexible. In comparison, plastic 3D printer can produce a plastic box or any other plastic part. In other words, additive manufacturing can increase the mass customization capability of the RMS. In this video https://youtu.be/Z6WQe1bf648 and in [45], we demonstrate how a flexible additive manufacturing in RMS in which a plastic 3D printer can print different parts automatically and a mobile robot pick up the 3D printer and move it to different places. In addition, we can use the manufacturing material more efficiently and produce less waste.

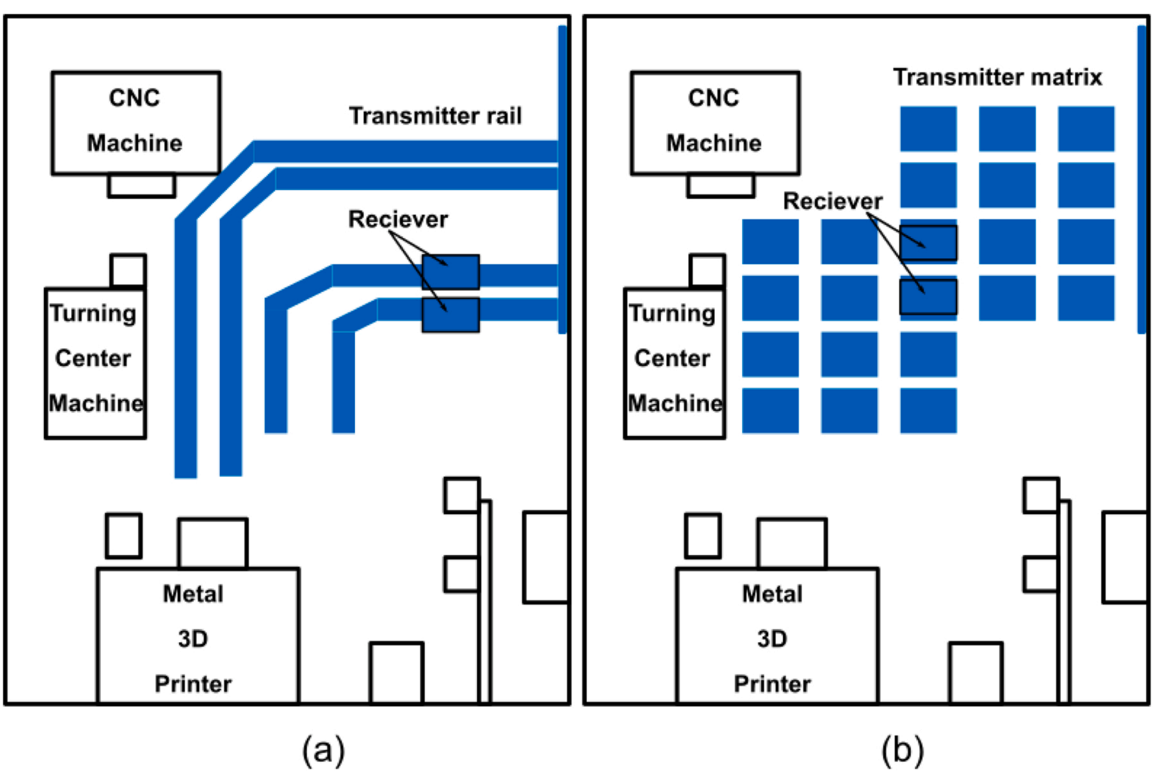

Fig. 4. A top-view of two approaches of dynamic WPT: (a) railway transmitters. (b) matrix transmitters.

3.3. Digital technologies

IIoT facilitates communication, allowing remote monitoring and control of the manufacturing system. Thus, we can retrofit the conventional manufacturing systems with IIoT to create communication between machines in the system. Besides, we can simulate the system to see how the reconfiguration and layout of the system will look in reality. The disadvantage of having only offline simulation is that we cannot test the RMS in real-time. It cannot be used for control or monitoring the RMS. In addition, the current solution for manufacturing systems is basic human-machine interfaces, where the labor communicates with the machines through a screen. This type of interface makes it difficult to program a reconfiguration of the manufacturing system.

However, if we use the digital twin of the system to test and see how the configuration looks and works. The digital twin is a real-time digital replica of the manufacturing system where we can transfer the data bidirectional between the physical and digital systems. Based on a digital twin we can simulate [46], control [47], monitor [48], predict failures of the system. In this paper, we simulate and monitor the system at the same time using a digital twin principle.

3.4. Smart RMS

Arnarson et al. [49] introduced industrial big data in RMS, for a smarter RMS system. In this work, they used the principles of industrial big data analysis moving towards automated RMS. Industrial big data analysis combined with artificial intelligence moves us toward a fully automated manufacturing system in which the system can manufacture any products without human intervention.

3.5. RMS with WPT

It is hard to achieve fully automated manufacturing systems with a conventional wired electrification approach. If we use WPT, we can gain autonomous electrification of the system and hence a fully automated system. Besides, WPT provides more flexibility and reliability to the RMS. In this section, we introduce the main concept of WPT to industry 4.0 technologies and give examples of static and dynamic implementation of WPT in RMS, while we provide more detailed descriptions and experimental results in further work.

The International Telecommunication Union defines WPT as the transmission of power from a power source to an electrical load wirelessly using a electromagnetic field [50]. WPT incorporates three main groups: near-field, mid-range, and far-field. The differences between these groups are in terms of the type of the electromagnetic wave, distance range, operating frequency level, power level, and the complexity of the system's architecture.

We can utilize either static or dynamic near-field WPT for RMS. The static approach offers electrification when the platforms are not moving. Fig. 3 illustrates three different scenarios. The arrows show the direction of the power flow. In scenario (a), we can fix the WPT transmitter-receiver on the platforms while electrifying each other through a mesh configuration. In contrast, in scenario (b), the platforms energize from a stationary machine, such as a turning center, while charging. The last scenario (c) is when the platform is not in use and charges from the main power source.

On the other hand, dynamic WPT can offer a power source for the platforms and mobile robots. We can implement the dynamic WPT through two approaches, namely, the railway approach and matrix one, as shown in Fig. 4. The railway transmitters provide continuous power to the platforms in the railway approach. However, the allocation of the platform should be predetermined, which limits the flexibility of the RMS. In contrast, the matrix approach offers a flexible charging solution. Nevertheless, it provides discrete charging, and hence we should optimize the distance between the transmitters, increasing the complexity and cost of the WPT system.

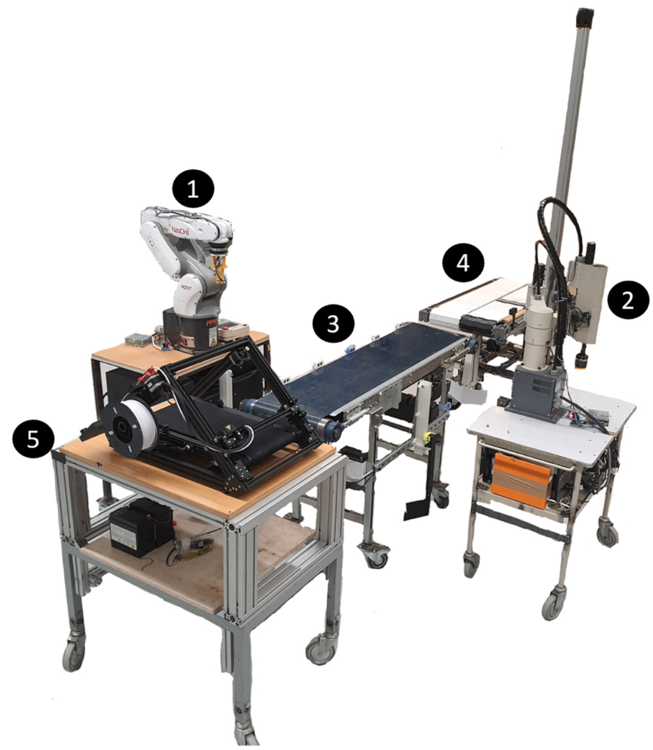

Fig. 5. The proposed RMS: (1) IRB1 platform, (2) IRB2 platform, (3) conveyor, (4) conveyor with lifting, and (5) 3D printer.

4. Reconfigurable manufacturing system

In this section, we describe the RMS and give a demonstration both by simulation and testing.

4.1. RMS description

Our system consists of five platforms:

- **IRB1 platform:** Has a four degree of freedom robot arm (SCARA-type). In this system it is used for simple assembly, pick and place and sorting operations.

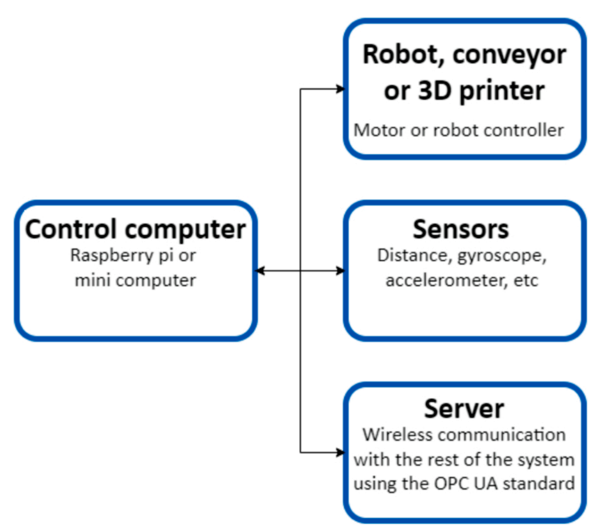

Fig. 6. The main components on each platform.

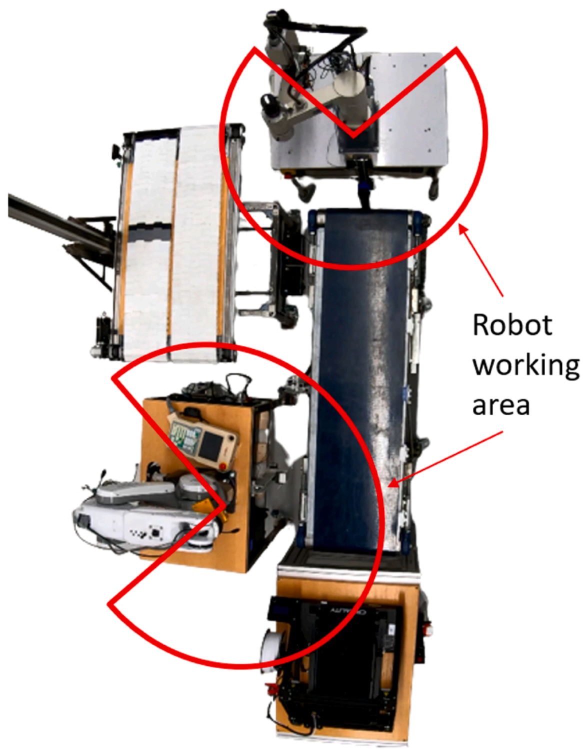

Fig. 7. An illustration of the placement requirements of the system.

- **IRB2 platform:** Is a six degree of freedom robot arm. The robot arm can be used for the same operations as the IRB1 robot, but can also do more complex tasks such as machine tending, polishing, etc.
- **Conveyor platform:** The conveyor platform is used to transport the parts between the robot arms.
- **Conveyor with lifting platform:** Is used to transport parts out of the manufacturing system. Since it has a lift module it is more adaptable then the conveyor platform.
- **3D printer platform:** The 3D print platform contains a Creality CR-30, which is a 3D printer that prints on a conveyor. It can automatically remove the parts as they are being printed.

Fig. 5 shows a specific setup of the RMS.

We have developed the platforms by retrofitting them with small single-board computers and sensors. We have used different sensors to measure distance, angular velocity, and acceleration. As the robot arms require a more powerful computer, we have used (i5–10210 U CPU) to run the inverse kinematics calculator in ROS MoveIT and image recognition models in parallel. While the conveyor, conveyor lift and 3D printer platform use a Raspberry pi for control. All the computers are equipped with WIFI for wireless communication and we have also utilized extra microcontrollers on some of the platforms to collect data and control motors. Fig. 6 depicts the setup of each platform.

A MiR100 mobile robot transports the platforms to the selected location. It has a carrying capacity of 100 kg and can pull up to 300 kg [51]. The accuracy of the mobile robot is $\pm$ 50 mm, which limits the flexibility of the system [12]. The low accuracy of the mobile robot can deteriorate the docking reliability of the platform. Nevertheless, a marker solution is used and enhance the docking accuracy of the mobile robot within $\pm$ 5 mm [51].

We can describe the docking sequence as follows: First, once the mobile robot reaches in front of the platform it adjust itself to the marker. Second, the marker moves up, so the mobile robot can drive under the platform. Third, the mobile robot drives forward with a fixed distance. Fourth, the hooking system is activated and fasten the mobile robot with the platform. A demonstration video to show the docking and uncoupling sequence can be fund at https://www.youtube.com/watch?v=RtOX0HGiqRs. When the mobile robot uncouples from a platform, the mobile robot software saves the platform's position. Besides, the mobile robot calculates and saves 1.5 m from the platform as the docking point for the mobile robot.

For communications the platforms are connected to the Open Platform Communications Unified Architecture (OPC UA). The OPC UA is a IEC 62541 standard and is used for communication in industrial applications [52]. It allows all platforms to connect to the same server and communicate seamlessly which facilitates the control of the robots, conveyors and other motors in the system. This communication protocol will also help to bring about machine-to-machine communication, and hence all platforms can operate without human intervention.

4.2. Platform placement

As mentioned in Section 2, reconfiguring of the RMS can be time consuming and often needs human labor. The idea behind this system is

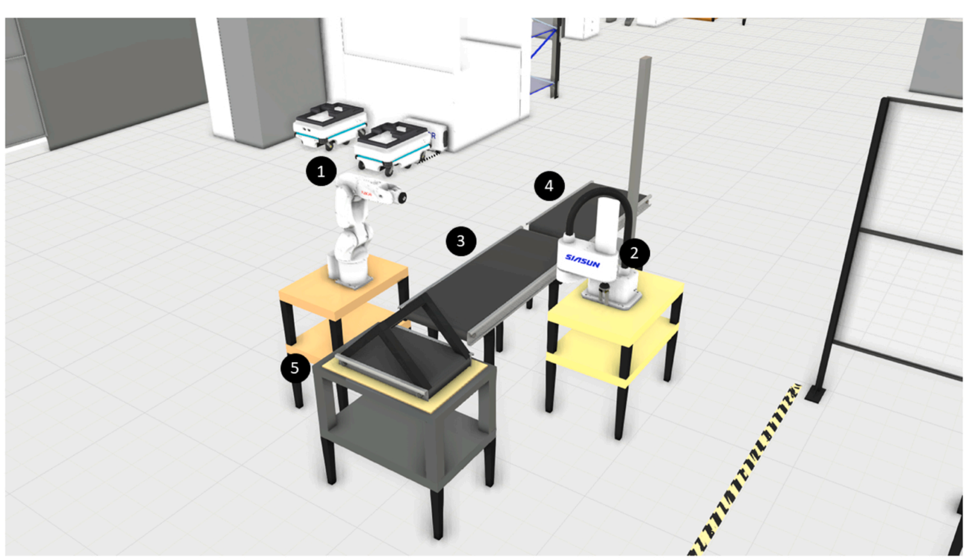

Fig. 8. A screenshot from Visual Components showing the digital twin of the platforms. (1) IRB1 platform, (2) IRB2 platform, (3) conveyor, (4) conveyor with lifting, and (5) 3D printer.

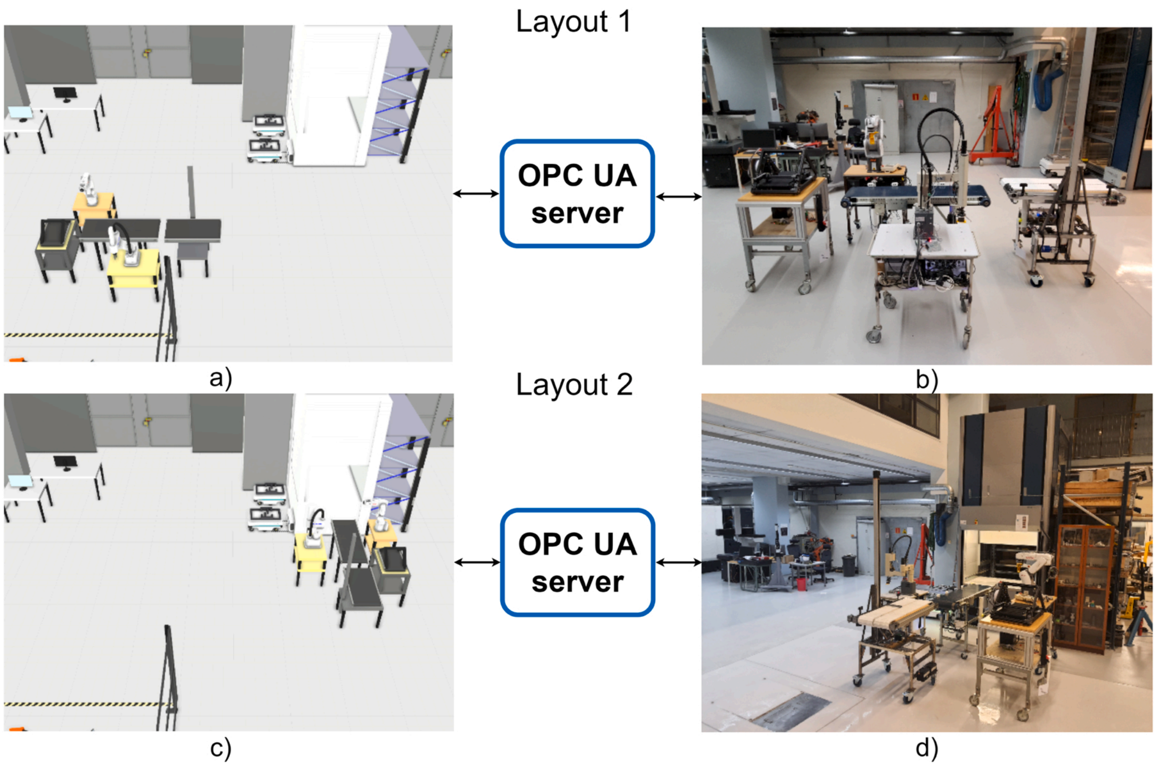

Fig. 9. Two layout configurations in the Visual Components (On the left side), and the resulting configuration assembled with the mobile robot (on the right side): a) The first digital layout. b) The first physical layout. c) The second digital layout. d) The second physical layout.

to reconfigure and change the system's layout automatically with a mobile robot. Also, we can change the layout of the system based on demands. However, the system still faces some challenges. For instance, the IRB1 robot has a movement radius of 0.6 m, while the IRB2 robot has a maximum reach of 0.9 m. For this system to work, the robot arms need to reach the platforms they are working with, as shown in Fig. 7, which add a constraint on system's arrangement. One way to tackle the challenges of choosing the layout of our system is by using a digital twin solution.

Van Der Horn et al. [53] have described the digital twin as a virtual representation of a physical system, where the virtual and physical systems share the data. The virtual model of the manufacturing system can be used to test and visually various configurations of the layout. We can also use it to send information about the placement of the platforms. In addition, we can combine a digital twin with a modular system to create fast reconfiguration, integration, and safety validation of the system [3].

Previously, Arnarson et al. [54] have developed a two-way digital twin model in the Visual Components Premium simulation software [55] and conducted laboratory testing of the system. As Visual Components Premium supports the OPC UA standard, we can use the digital twin model as a visual tool to plan the system's layout and simulate assembly and production flow for different system layouts. Fig. 8 shows the digital twin model of the five platforms. The model in the software has the same scales and positions of the components as the physical system. The simulation takes the positions of the digital platforms and sends them to the OPC UA server. The mobile robot can automatically get the new coordinates of the platforms and start moving them. Eventually, the simulation software decides how the mobile robot picks the platform.

4.3. Demonstrations of the RMS system

Two demonstrations show the functionality of our system.

Table 1
The time the mobile robot used to reconfigure both layouts measured in minutes.

	Layout 1	Layout 2
IRB1 Platform	2.2	2.2
IRB2 platform	2.2	2.3
Conveyor platform	2.1	2.9
Conveyor Lift	2.0	1.9
3D print platform	2.3	2.6
Total time [min]	10.8	11.8

4.3.1. Demonstration of simulation design

The first demonstration shows the automatic reconfiguration. Two layouts are created in the Visual Components model, and when the simulation is executed the positions of the platforms are sent to the server. Afterwards, the mobile robot reads the positions of the platforms from the OPC UA server and pick up and place the platform in the same position given by the model in Visual Components. The resulting configuration of the mobile robot can be seen in Fig. 9.

A video demonstration shows the functionality of the system and can be found at https://youtu.be/UXUlaawd8Ps with 5x speed and another video https://youtu.be/s8r-Q5eMy2M with normal speed. The purpose of the video is to showcase how the mobile robot can automatically change a manufacturing system's layout. The video starts with all platforms in different locations in the laboratory. Then mobile robot picks the platforms and places them into the configuration in Fig. 9. Second, the mobile robot takes apart the system and reconfigures a new manufacturing system with the vertical storage machine (Compact lift). The time it takes to move and place each platform and the total time of the configuration can be found in Table 1.

4.3.2. Demonstration of production simulation

In the second demonstration, we showcase the flexibility and reconfigurability of the system in the simulation model. For this experiment, we use the process modeling component of Visual

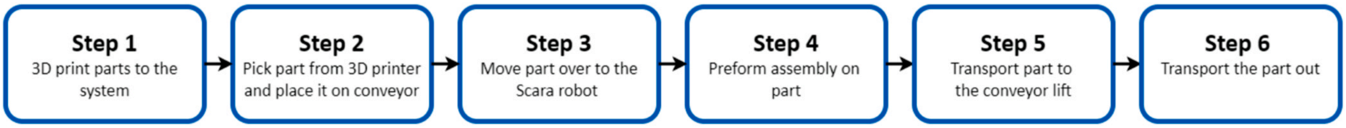

Fig. 10. The production sequence used to produce and assemble a box in the simulation.

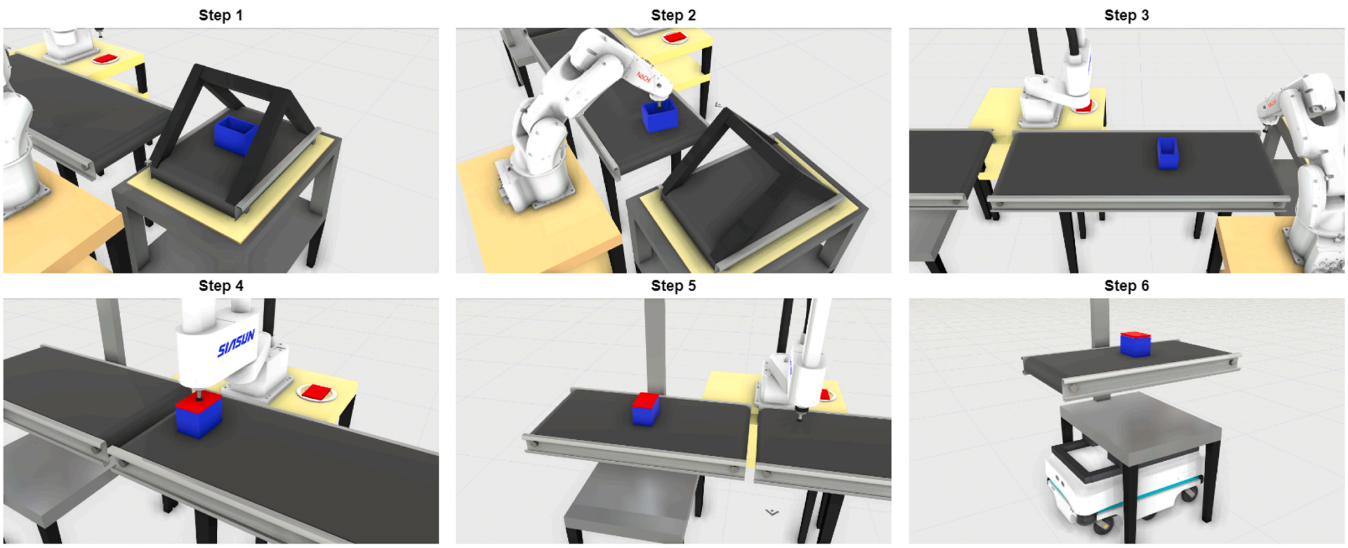

Fig. 11. An illustration of each step in the simulation.

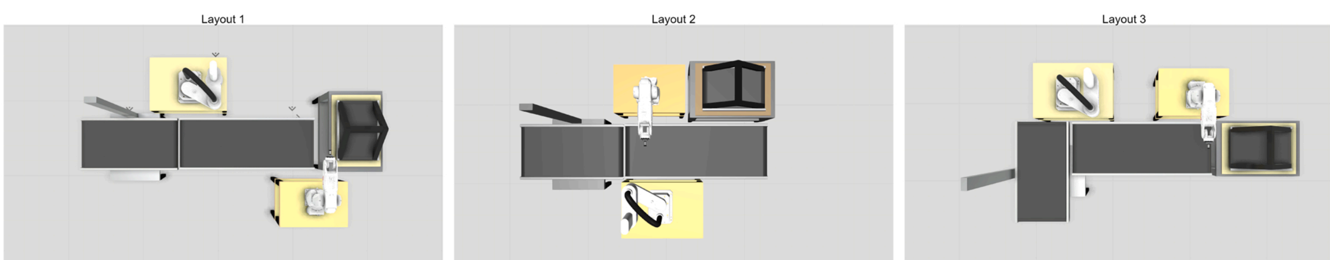

Fig. 12. Three different layout configuration to produce the box.

Table 2
The time it takes to complete each step in the simulation, without considering the 3D printing time measured in seconds.

Manufacturing setup	1	2	3
Step 1	4.6	4.6	4.6
Step 2	3.0	2.8	2.6
Step 3	11.3	2.4	9.8
Step 4	3.1	3.6	3.3
Step 5	10.1	9.5	2.9
Step 6	17.6	17.5	25.0
Total time [sec]	49.7	40.4	48.2

Components to program the system's movements. The simulation shows the production and assembling of a box in six steps, as shown in Fig. 10. The production process are: a box without a lid is 3D printed with the 3D printer platform. When the box reaches the end of the 3D printer, the IRB2 robot picks up the box and places it on the large conveyor. The conveyor transports the box to the IRB1 robot, which takes the lid and places it on top of the box. At last, the box is transported over to the conveyor lift, and the mobile robot transports the conveyor lift out. Fig. 11, illustrates all steps.

We can execute the same production plan of the box with different configurations and placement of the platforms. To test this, we create three different configurations, as can be seen in Fig. 12. A video demonstration https://youtu.be/6ir7RUN_uk0 of the three simulations shows a different production time for each layout. Table 2 lists the production times for each step in all three layouts. We can use the simulation to estimate the production time and test if there are any collisions in the simulation.

4.4. Demonstration of manufacturing application

To demonstrate a manufacturing application of the system, we simulate and implement an assembly of a manufacturing system around a CNC machine. In the simulation, the first step is to drag the platforms and rearrange them around the CNC machine. The second step is to check if the robot arms can reach the positions. The last step, using the digital twin we can transfer the positions of all the platforms to the mobile robot where it reconfigures the platforms automatically. Fig. 13 shows the demonstration of the proposed RMS for manufacturing application. The video https://youtu.be/vxsg4zgJzTU demonstrates the aforementioned three steps. The results shows the system needs around 12.75 min for rearranging around the CNC machine. In this demonstration, we can use one mobile robot to fill raw material to the CNC

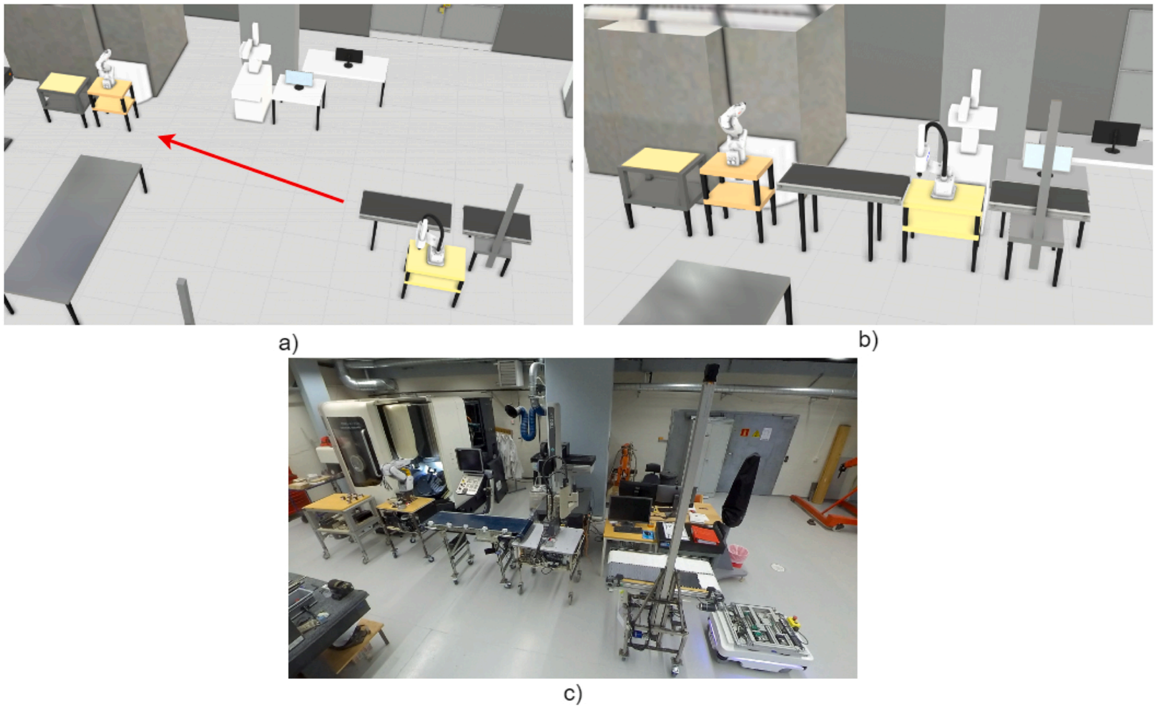

Fig. 13. Demostration of industrial application: a) Configuring the platforms around the CNC machine. b) Simulating to check that the robot arm can reach their position. c) The physical configuration of the platforms around the CNC machine.

machine, rearrange the system, and take out the manufactured products.

5. Discussion

Traditionally, RMS need human interaction to reconfigure the system. In this paper, we have proposed a new RMS solution that decreases the need for humans in the setup of a new manufacturing line. A mobile robot can reconfigure the platforms without any human intervention. A total reconfiguration of the system requires 10:8 min to (numerical range) 11:8 min depending on the layout.

We utilized additive manufacturing as an industry 4.0 technology to produce various products. We simulated three different layouts to manufacture a box using a 3D printer. According to the simulation, the production time took 49.7 s, 40.4 s, and, 48.2 s, respectively, without considering the 3D printing time. However, this was a simple example of producing one type of product, but the 3D printer can print any part as long as it fits within the dimensions of the 3D printer. Besides, using a 3D printer for production can easily automate the production process. Thus we create a platform with a 3D printer that can be controlled, operated, and monitored remotely.

Using industry 4.0 digital technologies, we retrofitted old machines with sensors and controllers, and by applying the IIoT, we got communication between all parts of the system. We used a two-way digital twin with simulation to program the system and choose the layout of the platforms. It gives the operator a simple drag and drop interface to position the platforms. We can also simulate the manufacturing process to test and see if the robot arm reaches its desired position. It creates a simple and intuitive interface for fast and simple programming of the layout.

The IIoT and digital twin can automate the system and put the building blocks for smart RMS. We can collect and store data from all platforms in real-time, which we can use to train machine learning algorithms to classify and predict the RMS. We can implement reinforcement learning and image recognition to create self adaptable control system for the robots. At the same time, we can apply image recognition models to detect when prints are failing or any other failure in the RMS.

Industry 4.0 technologies have enhanced the flexibility and reconfigurability of manufacturing systems by integrating robots, additive manufacturing, digital technologies, and smart RMS. However, we have several challenges that the proposed RMS is still facing.

The first challenge is to arrange the layout of the system in such a way that considering the limited working area of the robot arms. Currently, we address this challenge by simulation through a digital twin. However, we need to find a better solution to solve this problem autonomously. The second challenge is that the mobile robot needs extra force to move the trolleys and often ends up spinning while moving the platforms. In addition, if one of the ten wheels gets stuck, it will dramatically reduce the accuracy and cause collisions with other platforms. As a better solution, we can remove all wheels of the platforms and use a mobile robot with high lifting capacity. Then the mobile robot would be able to lift the platform and place them in different positions. Regardless of these challenges, the system has a unique characteristic that can not only be reconfigured in different layouts but can also be rearranged in other locations irrespective of the manufacturing space.

We also proposed WPT systems to electrify the platforms and increase the flexibility of the manufacturing system. In addition, we can utilize static or dynamic WPT to electrify the system. The dynamic WPT can electrify both the platforms and the mobile robot, increasing the system's extent and cost. In contrast, static WPT offers a good option to electrify the platforms from each other or a main fixed machine. The system will get better efficiency by correcting the misalignment between the platforms.

6. Conclusion

We have proposed a number of industry 4.0 technologies to build an highly flexible RMS. We also expand the industry 4.0 technologies principle by adding WPT. The WPT system increases the flexibility and reliability of the proposed RMS. Our system includes five platforms containing robot arms, a conveyor belt, a conveyor lift, and a 3D printer. We have retrofitted the platforms and used a mobile robot to reconfigure the platforms automatically. Then, we created a simulation model that controls and arranges the platforms using the digital twin to configure the system. The simulation model has the same scale and coordinates as the mobile robot. Using the OPC UA server, we send the coordinates of the platforms from the simulation model to the physical model. In addition, we present two demonstrations: the first simulation showing the system's flexibility with the production and assembly of a box, and the second simulation showing how the mobile robot can reconfigure the platforms based on the simulation model.

7. Future works

The proposed system can be further expanded and automated.

7.1. Automatic layout design

As can be seen from the simulation results, there are multiple solutions for positioning the platforms. Therefore, optimizing the layout with the shortest path or smallest area can reduce manufacturing time and costs. We seek to develop a mathematical model that can find a sub-optimal layout for a system with multiple platforms as further work. With the mathematical model, the system will rearrange the layout automatically depending on what we need to manufacture.

7.2. Automatic programming/control

Another challenge facing the system is to control and program the platforms automatically. Due to the mobile robot inaccuracy, the platforms aren't positioned with high accuracy. Therefore, using pre-programmed programs on the robot arms will not be feasible. Besides, the literature has previously shown that manually controlling, programming, and setting up the system is time-consuming, requiring expertise in control systems [5]. We will investigate and create a system that can be programmed automatically depending on what will be manufactured.

7.3. Wireless electrification of RMS

Finally, we will study in detail different approaches of WPT and examine capacitive power transfer (CPT) as a low-cost solution for powering the RMS. In addition, we expand the system with a mobile battery platform that can power other platforms using CPT.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Fathi M, Ghobakhloo M. Enabling mass customization and manufacturing sustainability in industry 4.0 context: a novel heuristic algorithm for in-plant material supply optimization. Sustainability 2020;12(16).
[2] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. J Manuf Syst 2010;29(4):130–41. https://doi.org/10.1016/j.jmsy.2011.01.001.
[3] Malik AA, Masood T, Kousar R. Reconfiguring and ramping-up ventilator production in the face of covid-19: Can robots help? J Manuf Syst 2021;60:864–75.
[4] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, et al. Reconfigurable manufacturing systems. CIRP Ann 1999;48(2):527–40. https://doi.org/10.1016/S0007-8506(07)63232-6.
[5] Kim DY, Park JW, Baek S, Park KB, Kim HR, Park JI, et al. A modular factory testbed for the rapid reconfiguration of manufacturing systems. J Intell Manuf 2020;31(3):661–80. https://doi.org/10.1007/s10845-019-01471-2.
[6] Putnik G, Sluga A, ElMaraghy H, Teti R, Koren Y, Tolio T, et al. Scalability in manufacturing systems design and operation: state-of-the-art and future developments roadmap. CIRP Ann 2013;62(2):751–74. https://doi.org/10.1016/j.cirp.2013.05.002. ⟨https://www.sciencedirect.com/science/article/pii/S0007850613001923⟩.
[7] Klingenberg CO, Borges MAV, Antunes Jr JAV. Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies. J Manuf Technol Manag 2021;32(3, SI):570–92. https://doi.org/10.1108/JMTM-09-2018-0325.
[8] Singh A, Gupta P, Asjad M. Reconfigurable manufacturing system (rms): Accelerate towards industries 4.0. Proc Int Conf Sustain Comput Sci, Technol Manag (SUSCOM) 2019;01. https://doi.org/10.2139/ssrn.3354485.
[9] Bortolini M, Galizia FG, Mora C. Reconfigurable manufacturing systems: Literature review and research trend. J Manuf Syst 2018;49:93–106. https://doi.org/10.1016/j.jmsy.2018.09.005. ⟨https://www.sciencedirect.com/science/article/pii/S0278612518303650⟩.
[10] Maganha I, Silva C, Ferreira LMDF. The layout design in reconfigurable manufacturing systems: a literature review. Int J Adv Manuf Technol 2019;105(1–4):683–700. https://doi.org/10.1007/s00170-019-04190-3.
[11] Morgan J, Halton M, Qiao Y, Breslin JG. Industry 4.0 smart reconfigurable manufacturing machines. J Manuf Syst 2021;59:481–506. https://doi.org/10.1016/j.jmsy.2021.03.001.
[12] H. Arnarson, B. Solvang, 2022. Reconfigurable autonomous industrial mobile manipulator system, in: 2022 IEEE/SICE International Symposium on System Integration (SII), 2022, 772–777.10.1109/SII52469.2022.9708887.
[13] D. Sanderson, J. C. Chaplin, L. De Silva, P. Holmes, S. Ratchev, 2016. Smart manufacturing and reconfigurable technologies: Towards an integrated environment for evolvable assembly systems, in: 2016 IEEE 1st International Workshops on Foundations and Applications of Self* Systems (FAS*W), 2016, 263–264.10.1109/FAS-W.2016.61.
[14] SMC, SMC International Training – The didactic division of SMC Corporation, [Online; accessed 3. Feb. 2022] (Feb 2022). ⟨https://www.smctraining.com⟩.
[15] Madsen O, Møller C. The aau smart production laboratory for teaching and research in emerging digital manufacturing technologies. Procedia Manuf 2017;9:106–12. https://doi.org/10.1016/j.promfg.2017.04.036. 7th Conference on Learning Factories, CLF 2017.
[16] daCunha C, Cardin O, Gallot G, Viaud J. Designing the digital twins of reconfigurable manufacturing systems: application on a smart factory. IFAC-Pap 2021;54(1):874–9. https://doi.org/10.1016/j.ifacol.2021.08.103. 17th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2021.
[17] U. of Wisconsin, IMS Centre Laboratories | Intelligent Manufacturing Systems (IMS) Centre, [Online; Accessed 2. Feb. 2022] (Feb 2022). ⟨https://www.uwindsor.ca/intelligent-manufacturing-systems/299/ims-centre-laboratories⟩.
[18] N. Jäpel, Industrie 4.0 Modellfabrik, [Online; accessed 2. Feb. 2022] (Feb 2022). https://www.htw-dresden.de/hochschule/fakultaeten/info-math/forschung/smart-production-systems/industrie-40-modellfabrik.
[19] Festo, CP Factory - The Cyber-Physical Factory, [Online; accessed 5. Feb. 2022] (Feb 2022). ⟨https://www.festo-didactic.com/int-en/learning-systems/learning-factories,cim-fms-systems/cp-factory/cp-factory-the-cyber-physical-factory.htm?fbid=aW50LmVuLjU1Ny4xNy4xOC4xMjkzLjc2NDM⟩.
[20] Adamietz R, Giesen T, Mayer P, Johnson A, Bibb R, Seifarth C. Reconfigurable and transportable container-integrated production system. Robot Comput-Integr Manuf 2018;53:1–20. https://doi.org/10.1016/j.rcim.2018.02.008. ⟨https://www.sciencedirect.com/science/article/pii/S0736584517301515⟩.
[21] Kang HS, Noh SD, Son JY, Kim H, Park JH, Lee JY. The FaaS system using additive manufacturing for personalized production. RAPID Prototyp J 2018;24(9):1486–99. https://doi.org/10.1108/RPJ-11-2016-0195.
[22] H. Cheng, H. Chen, Y. Liu, Object handling using autonomous industrial mobile manipulator, in: 2013 IEEE International Conference on Cyber Technology in Automation, Control and Intelligent Systems, 2013, 36–41.10.1109/CYBER.2013.6705416.
[23] Hvilshoj M, Bogh S, Nielsen OS, Madsen O. Autonomous industrial mobile manipulation (AIMM): past, present and future. Ind ROBOT- Int J Robot Res APPLICATION 2012;39(2):120–35. https://doi.org/10.1108/01439911211201582.
[24] Inoue S, Urata A, Kodama T, Huwer T, Maruyama Y, Fujita S, et al. High-precision mobile robotic manipulator for reconfigurable manufacturing systems. Int J Autom Technol 2021;15(5):651–60. https://doi.org/10.20965/ijat.2021.p0651.
[25] Andersen RE, Hansen EB, Cerny D, Madsen S, Pulendralingam B, Bøgh S, et al. Integration of a skill-based collaborative mobile robot in a smart cyber-physical environment. Procedia Manuf 2017;11:114–23. https://doi.org/10.1016/j.promfg.2017.07.209. 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27-30 June 2017, Modena, Italy.
[26] Singh A, Gupta S, Asjad M, Gupta P. Reconfigurable manufacturing systems: journey and the road ahead. Int J Syst Assur Eng Manag 2017;8(2, 2):1849–57. https://doi.org/10.1007/s13198-017-0610-z.
[27] Khanna K, Kumar R. Reconfigurable manufacturing system: a state-of-the-art review, BENCHMARKING-AN. Int J 2019;26(8):2608–35. https://doi.org/10.1108/BIJ-05-2018-0140.
[28] R. Pansare, G. Yadav, M.R. Nagare, Reconfigurable manufacturing system: a systematic review, meta-analysis and future research directions, JOURNAL OF ENGINEERING DESIGN AND TECHNOLOGY 10.1108/JEDT-05–2021-0231.
[29] Song C, Ding Y, Eid A, Hester JGD, He X, Bahr R, et al. Advances in wirelessly powered backscatter communications: From antenna/rf circuitry design to printed

flexible electronics. Proc IEEE 2022;110(1):171–92. https://doi.org/10.1109/JPROC.2021.3125285.
[30] Psomas C, You M, Liang K, Zheng G, Krikidis I. Design and analysis of swipt with safety constraints. Proc IEEE 2022;110(1):107–26. https://doi.org/10.1109/JPROC.2021.3130084.
[31] Qu X, Zhang W, Wong S-C, Tse CK. Design of a current-source-output inductive power transfer led lighting system. IEEE J Emerg Sel Top Power Electron 2015;3(1):306–14. https://doi.org/10.1109/JESTPE.2014.2318045.
[32] Jiang C, Chau KT, Leung YY, Liu C, Lee CHT, Han W. Design and analysis of wireless ballastless fluorescent lighting. IEEE Trans Ind Electron 2019;66(5):4065–74. https://doi.org/10.1109/TIE.2017.2784345.
[33] Han W, Chau KT, Jiang C, Liu W, Lam WH. High-order compensated wireless power transfer for dimmable metal halide lamps. IEEE Trans Power Electron 2020;35(6):6269–79. https://doi.org/10.1109/TPEL.2019.2950206.
[34] Han W, Chau KT, Zhang Z. Flexible induction heating using magnetic resonant coupling. IEEE Trans Ind Electron 2017;64(3):1982–92. https://doi.org/10.1109/TIE.2016.2620099.
[35] Zhang Y, Yang J, Jiang D, Li D, Qu R. Design, manufacture, and test of a rotary transformer for contactless power transfer system. IEEE Trans Magn 2022;58(2):1–6. https://doi.org/10.1109/TMAG.2021.3094135.
[36] Zhang Z, Chau KT, Qiu C, Liu C. Energy encryption for wireless power transfer. IEEE Trans Power Electron 2015;30(9):5237–46. https://doi.org/10.1109/TPEL.2014.2363686.
[37] Zeng Y, Rong C, Lu C, Tao X, Liu X, Liu R, et al. Misalignment insensitive wireless power transfer system using a hybrid transmitter for autonomous underwater vehicles. IEEE Trans Ind Appl 2022;58(1):1298–306. https://doi.org/10.1109/TIA.2021.3110496.
[38] Wang D, Cui S, Zhang J, Bie Z, Song K, Zhu C. A novel arc-shaped lightweight magnetic coupler for auv wireless power transfer. IEEE Trans Ind Appl 2022;58(1):1315–29. https://doi.org/10.1109/TIA.2021.3109839.
[39] Wu P, Xiao F, Huang H, Sha C, Yu S. Adaptive and extensible energy supply mechanism for uavs-aided wireless-powered internet of things. IEEE Internet Things J 2020;7(9):9201–13. https://doi.org/10.1109/JIOT.2020.3005133.
[40] Wei Z, Yu X, Ng DWK, Schober R. Resource allocation for simultaneous wireless information and power transfer systems: a tutorial overview. Proc IEEE 2022;110(1):127–49. https://doi.org/10.1109/JPROC.2021.3120888.
[41] Liu W, Chau KT, Lee CHT, Cao L, Han W. Wireless power and drive transfer for piping network. IEEE Trans Ind Electron 2022;69(3):2345–56. https://doi.org/10.1109/TIE.2021.3068675.
[42] Covic GA, Boys JT. Modern trends in inductive power transfer for transportation applications. IEEE J Emerg Sel Top Power Electron 2013;1(1):28–41. https://doi.org/10.1109/JESTPE.2013.2264473.
[43] Guidi G, Suul JA, Jenset F, Sorfonn I. Wireless charging for ships: High-power inductive charging for battery electric and plug-in hybrid vessels. IEEE Electrif Mag 2017;5(3):22–32. https://doi.org/10.1109/MELE.2017.2718829.
[44] Ahmad A, Alam MS, Chabaan R. A comprehensive review of wireless charging technologies for electric vehicles. IEEE Trans Transp Electrif 2018;4(1):38–63. https://doi.org/10.1109/TTE.2017.2771619.
[45] H. Arnarson, B. Solvang, 2022. Reconfigurable 3d printing platform for warehouses, in: 2022 6th International Conference on Green Technology and Sustainable Development (GTSD 2022), (Accepted), 2022, 772–777.
[46] H. Arnarson, 2022. Demonstration of production simulation, [Online; accessed 7. Feb. 2022] (Feb 2022). https://youtu.be/6ir7RUN_uk0.
[47] H. Arnarson, 2022. Super flexible reconfigurable manufacturing system (5x speed), [Online; accessed 21. Feb. 2022] (FEB 2022). https://youtu.be/UXUlaawd8Ps.
[48] H. Arnarson, 2022. Digital twin labratory using open access middleware for real-time communication and cooperation, [Online; Accessed 24. Mar. 2022] (MAR 2022). https://www.youtube.com/watch?v=HXskVx1IVyg.
[49] H. Arnarson, B. A. Bremdal, B. Solvang, 2022. Reconfigurable manufacturing: Towards an industrial big data approach, in: 2022 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), (Accepted), 2022.
[50] ITU-R Recommendation ITU-R SM.2110, Frequency ranges for operation of non-beam wireless power transmission systems, Available at ⟨https://www.itu.int/rec/R-REC-SM.2110–0-201709-S⟩ (2021/ 11/09).
[51] M. I. Robots, 2022. Mobile robot from mobile industrial robots - mir100, [Online; accessed 27. Jan. 2022] (Jan 2022). https://www.mobile-industrial-robots.com/solutions/robots/mir100.
[52] O. Foundation, Unified architecture, [Online; accessed 04. Feb. 2022].⟨https://opcfoundation.org/about/opc-technologies/opc-ua/⟩.
[53] VanDerHorn E, Mahadevan S. Digital twin: Generalization, characterization and implementation. Decis Support Syst 2021;145:113524. https://doi.org/10.1016/j.dss.2021.113524.
[54] H. Arnarson, B. Solvang, B. Shu, 2020. The application of open access middleware for cooperation among heterogeneous manufacturing systems, in: 2020 3rd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS), 2020, 1–6.10.1109/SIMS49386.2020.9121537.
[55] Visual Components, Visual Components Premium - Visual Components, [Online; accessed 27. Jan. 2022] (Jan 2022). ⟨https://www.visualcomponents.com/products/premium⟩.