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AI-enhanced cooperating robots for reconfigurable manufacturing of large parts

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Abstract: Large parts manufacturing involves the production of low batch, possibly one-of-a-kind, components of high cost and complexity. Industry specific knowledge and skills are converging to the technological evolution brought by Industry 4.0 where ICT and automation boost productivity and product quality. This paper presents an approach towards assembly of large-scale parts, where the synergy of robots, human skills and ICT tools enable flexible production. High payload collaborative robots and mobile manipulators facilitate handling, exoskeletons and AR tools relieve the workers' physical and cognitive stress, VR tools improve the workplace design, while the cell's Digital Twin facilitates decision making.

Keywords: Large-scale parts assembly, Human-Robot collaboration, Flexible and reconfigurable manufacturing, exoskeletons, Human operator support, Human centred automation, assembly and disassembly

1. INTRODUCTION

Manufacturing is one of the critical activities affecting nations' prosperity (Chryssolouris, 2006). Large-scale parts production is an integral part of several manufacturing sectors, such as aeronautics, shipbuilding, oil and gas, construction, etc. which greatly impact the global economy. Indicatively it is reported that the worth of the long fiber thermoplastics market will reach $4.6 billion by 2025 (Markets and markets, 2019). The common characteristic of these sectors is that the orders are usually 'one-of-a-kind' or demand low volume production of highly customized parts. The corresponding manufacturing processes are complex requiring craftsmanship, knowledge, and skills.

The manufacturing methodologies of large-scale parts are typically based on the highly skilled workforce to fulfil precision and quality requirements. Focusing on the handling, locating, and assembly of large-scale parts, fixtures and other types of product-specific equipment are usually employed, resulting in the increase of the necessary set-up times. The weight balancing on cranes and rail tracks is often performed empirically, hence the transportation of the heavy parts might be unstable entailing accidents and potential injuries of the workers. Also, in the case of lengthy parts, over-constrained clamping systems are often utilized to prevent weight deformations while the prevention of the part's distortion relies on the operator's experience (Uriarte *et al.*, 2013). Although, there is equipment that could improve the performance of the processes by controlling the location and exerted forces (Estévez, Rodríguez and Ayesta, 2018) the order's batch size, and hence the Return-of-Investment frequently undermines the economic feasibility of such investments. The production scheduling and the reaction to abnormal situations, e.g. defective parts, require tools to enable dynamic adaptation to changes based on production-related data (Mourtzis, Zogopoulos and Xanthi, 2019).

However, as technology advances new capabilities are offered concerning both the connectivity of the resources and the implementation of robotics and automation for flexible manufacturing (Makris, 2021). In this context, a wide range of solutions has been developed aiming to boost productivity, address global market demand fluctuations and provide highly customized products in low delivery times. For instance, Internet of Things has been utilized to enable monitoring the actual status of the resources (Prathima, Sudha and Suresh, 2020), and facilitate adaptive shop-floor scheduling (Zhou *et al.*, 2021). The reconfiguration of shopfloors including autonomous production units (Michalos *et al.*, 2016), as well as the supply operations using mobile robots have been investigated (Kousi, Koukas, *et al.*, 2019). The reduction of additional costs of fixtures has been addressed with the concept of cooperating robots for fixtureless assembly (Aivaliotis, Michalos and Makris, 2018) and reconfigurable grippers (Spiliotopoulos, Michalos and Makris, 2018).

The existing developments need to be adapted to the special challenges of large-scale parts characteristics to be exploited in their manufacturing. The high complexity of the processes and the uniqueness of the parts call for high flexibility, which can be achieved thanks to the intelligence, intuition, and versatile problem solving of the human workers (Wang *et al.*, 2019). Hence, the human should be kept in the loop and any of the adopted developments should aim to reinforce their capabilities. Applications that are capable of providing the necessary information at the right time can reduce the workers' cognitive stress (Alexopoulos *et al.*, 2018). Furthermore, the assembly of highly customized sophisticated parts often involves product modifications leading to re-scheduling (Rochow *et al.*, 2015), thus providing updated instructions is

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critical for the efficiency of the process (Mourtzis, Zogopoulos and Xanthi, 2019). The physical stress of the workers can be relieved by employing robotic resources. The robots' strength, precision, and repeatability with the workers' intelligence may be exploited towards higher product quality and reduced delivery times. Human-Robot Collaboration (HRC) has been proposed frequently for assembly operations in the automotive sector (Michalos *et al.*, 2018; Hietanen *et al.*, 2020). Furthermore, the use of exoskeletons, a newly emerging technology in the manufacturing field, has been proposed to relieve physical strain (Karvouniari *et al.*, 2018).

This work aims to introduce an approach towards the flexible and high precision assembly of large-scale parts, which is based on the synergy of robotic resources, human workers, and ICT tools. Precision handling is enhanced by high payload collaborative robots and mobile manipulators (Fig. 1). The mental and physical workload of the workers is preserved low thanks to exoskeletons (Fig. 1) and AR tools. VR tools support the workspace design by providing more realistic simulations and enable offline training, while the Digital Twin (DT) of the cell provides context to support decision making.

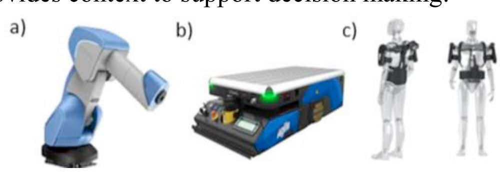

Fig. 1. a) High payload collaborative robot, b) Mobile platform and c) Upper-limb exoskeleton (https://www.comau.com/en)

The remainder of the paper is structured as follows. Section 2 analyses the approach towards flexible assembly of large-scale parts using autonomous robots and operator support systems, Section 3 proposes a potential implementation while Section 4 discusses the expected outcomes. Finally, in Section 5 the authors discuss their conclusions and shape their future work.

2. HRC ENABLED ASSEMBLY OF LARGE PARTS

This section analyses the approach HRC towards flexible assembly of large-scale parts by describing the added value of the solution's standalone modules. Fig. 1 depicts an overall mapping of the large parts assembly characteristics and challenges to the various tools that are proposed under a new HRC paradigm.

2.1 Multi-type and multi-purpose robots for HRC

The underlying concept of the proposed approach is to facilitate heavy parts handling with satisfactory precision, by allocating physically intense tasks to robot manipulators, and tasks of high dexterity and intelligence to humans, while providing support to relieve any physical strain. In more detail:

a. Cable-driven robots can transport extremely large and heavy parts while being autonomously navigated on the shop floor avoiding obstacles and speeding up transportation. They can also perform automatic clamping, eliminating the time that is currently spent to secure the parts in fixtures.
b. High payload collaborative manipulators, e.g. AURA (Fig. 1), can manipulate and assembly various parts of high dimensions and weight. They exhibit high repeatability and precision, so they can improve processes whose quality is currently dependent on the operator's performance. Also, by being equipped with sensors and adaptive gripping devices for collaborative manipulation, they can enable high levels of flexibility.

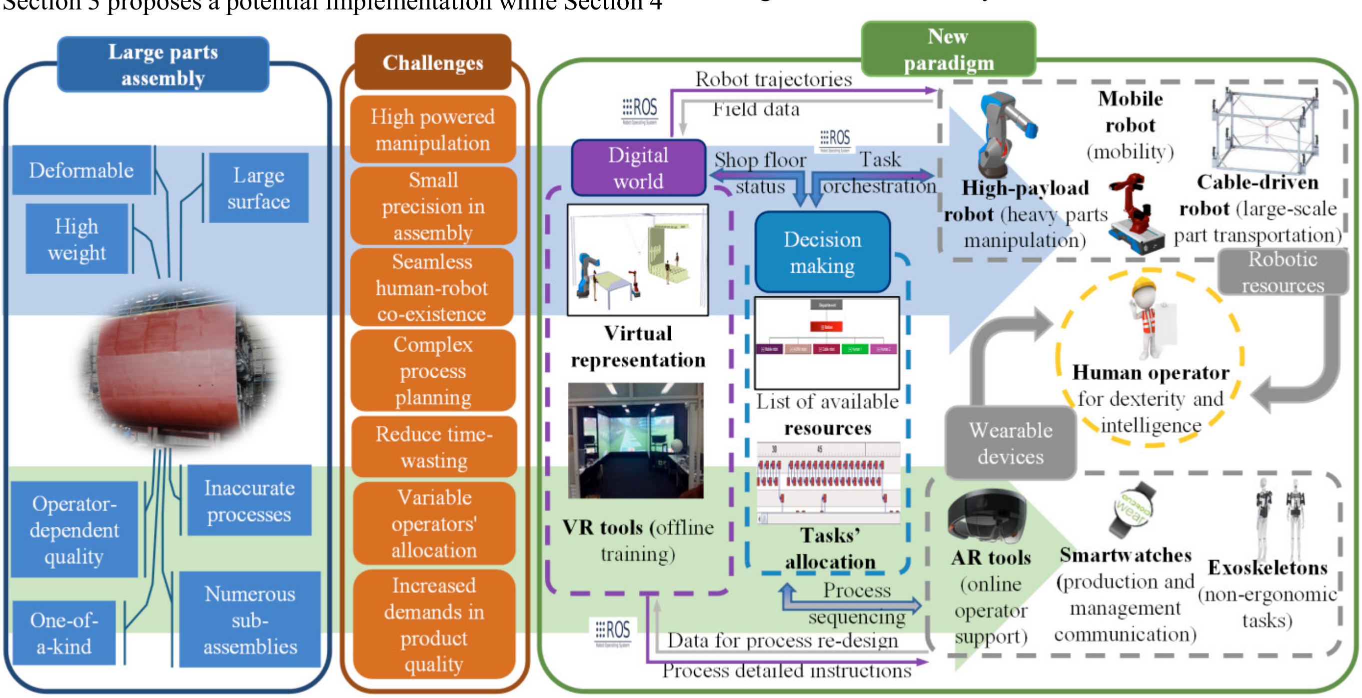

Fig. 2. Overall mapping of the proposed approach

c. Mobile manipulators (Fig. 1) can assist workers by providing them with parts, or tools, and by performing tasks of high repeatability or restricted accessibility.
d. Upper-limb exoskeleton devices (Fig. 1), which can adapt to the user's morphology and the tasks requirements, may reduce physical strain in non-ergonomic postures.

2.2 AR tools and wearable devices for operator support

The integration of AR technologies and wearable devices such as smartwatches can provide operator-friendly solutions with high customization potential. Their main contribution is to support the operator in real-time during the various assembly processes, by providing different kinds of information in the following different format types based on the particularities of the product, process, and operator:

- 3D part superposition atop real components to indicate proper assembly for precise part positioning
- Process animations for complex procedures involving the manipulation of high cost – fragile components
- Text-based or visual representation of correct process parameters to be used in each task
- Workspace, trajectory, and safely monitored areas where robots operate to minimize uncertainty
- Audio cues and alerts for enhanced awareness of the operational safety status
- Simple feedback provision functionalities such as virtual buttons to confirm undertaken activities.

The use of such devices extends further as thanks to their built-in sensors and communication capabilities, they can contribute to the efficient process control as well as providing feedback to operators from errors detected on the shop floor. These can be an indispensable function for populating DT with real-time data concerning shop-floor status, robot/operator status, etc., and enabling autonomy in decision making at the resource/ station/ line control levels.

The integration of the AR-based tools may involve either the use of officially provided hardware devices to the operators for in-house use or the "bring your own device" policy, where the workers are allowed to connect to a local network of the company's ICT system by using their own devices. Accessing the network from outside of the company should not be allowed. In both cases, each user can be assigned a specific role, enabling the security to be embedded by associating the designed security levels to the involved roles.

2.3 Simulation based process design and optimization

The complex design and characteristics of large-scale parts make it difficult to accurately predict and handle process deviations. In this direction, DT can be used as an accurate virtual world representation of the production system including all information related to humans, robotics resources, and any of the aforementioned supporting technologies. The real-time update of this DT with data feeds from shop floor sensors, MES/ERP systems and the individual controllers of each production resource enables the offline formulation and evaluation of alternative task planning and reconfiguration scenarios. In this sense, autonomy in decision making can be achieved at different levels including but not limited to the following scenarios:

- Task allocation between operators, robots and other resources considering both human ergonomics and production performance criteria.
- Layout configuration selection through automated 3D simulation of the assembly process performance using an extension to software such as DELMIA or Process Simulate.
- Robotic operations verification using detailed material simulation techniques. An example would the trajectory planning considering material deformation.
- Production scheduling for accommodating the customized requirement of each unique product by the system resources.

The above list is of course non exhaustive as the data obtained by the DT can be available to any type of simulation/ optimization tool that can be used to provide relevant assessments. Navigation planners for mobile robots, monitoring tools for human intention recognition and orchestrators for Human Robot Collaborative tasks are some of the examples that can be enabled. As for the corresponding software architecture, it can be based on paradigms such as the one presented by Kousi, Gkournelos, *et al.* (2019).

2.4 VR tools for ergonomics optimization & offline training

On top of the simulation models and tools described in the previous section, Virtual Reality (VR) tools can be beneficial by providing support to both the worksplace design engineers, and workers. VR allows engineers to perform workplace evaluation and redesign in immersive environments exploiting the highly realistic visualization. In addition, it is possible to track and analyse the movement and postures of the workers before the actual workplace is commissioned, and identify whether redesign is needed based on methods assessing the ergonomics, such as RULA (Middlesworth, 2012) and MURI (Ani, Kamaruddin and Azid, 2019), as well as on methods related to lean manufacturing (e.g. Value Stream Mapping). The incorporation of tools to automatically perform these assessments in the VR environment greatly simplifies the evaluation process, reducing downtime and affiliated costs.

On the other hand, the workers have the chance to be trained offline and learn how to avoid bad postures or health injuries without stalling the production or being stressed that they might undermine the products quality. VR implementation may involve 3-wall CAVE or head mounted devices.

3. CASE STUDY

This section focuses on the assembly of a bus describing the current workflow, its pain points, and the envisaged solution.

A bus structure comprises 6 sub-assemblies: the roof, chassis, left and right sidewalls, cabin, and tail frames. Each of those consists of a series of steel profiles/panels welded to each other. Following the manufacturing of the sub-assemblies, the roof is placed on the top of the sidewalls, and the cabin and tail to the front and back bus ends, respectively. This sub-assembly is joined to the chassis, and the whole structure is galvanized and painted. Next, the operators mount on the bus structure the cabling, electric equipment, and control, but also windows, doors, internal decoration elements (e.g. floor, curtains, etc.), the bus engine, and the suspension system. Usually, a bus order includes 10 to 100 buses that are of the same design and configuration. However, each bus is configured differently thanks to the combination of several available selections on bus length, the number of doors, and engine type, but also to customer-specific requirements (electric components, internal decoration, etc.). Thus, each order is considered as a different project which however needs to be performed in the same place as the rest of the orders.

The pre-treatment and joining of the standalone frames are currently highly dependent on human performance. Overhead cranes, trucks, and trolleys are used for heavy parts transportation. Even though extra time is spent to secure the parts via belts and fixtures, the lengthy and slender frames tend to distort and chatter during transportation. Also, the frames' dimensions might deviate from the target tolerances inducing reworks, rescheduling of tasks, as well as extra materials and tools to complete the assembly. As for the assembly, it usually involves overhead work, kneeling and squatting which in the long term can cause musculoskeletal disorders.

The envisaged solution based on the enabling technologies described in Section 2, is illustrated in Fig. 3. The implementation of the approach includes a set of robotic resources ((1), (4), (5), (6)), (8) safety monitoring devices for human-aware robot motion, sensors for quality inspection (3), AR-based tools (7) and wearable devices (2) to support humans during the manufacturing tasks execution, and HRC.

The solution's layout is designed via simulations and immersive environments, enabling to evaluate its effectiveness in terms of ergonomics and lean manufacturing principles (Ani, Kamaruddin and Azid, 2019). The virtual model of the workstation is updated throughout the workstation's lifecycle with field data, so that the DT of the workstation can be used for decision making and optimization during the workstation's lifecycle e.g. process sequencing, workplace layout, robot trajectories, error recovery due to low process quality or equipment failure etc. In more detail, in the case of the mobile robot's navigation the constantly updated virtual shopfloor is used to provide context to the navigation algorithm for the planning of collision-free paths. The virtual shopfloor is modelled in a software package such as Gazebo which allows to interface (via ROS services) with the shopfloor sensors (laser scanners, safety mats, odometry sensors, etc.), and update the position of resources, obstacles, and workers in the virtual model of the shopfloor according to the collected data.

The mobile robot can perform several operations such as welding, inspection. It can also bring materials and tools to the workers ensuring that they are available the right time at the right place. The mobile robot can perform the welding tasks, as long as the human is at a safe distance from the workstation, increasing the repeatability and precision of the process. At the same time, the intelligence, and perceptive abilities of the human can be exploited for the pre-treatment of the parts that the robot will process. Wearables ensure that any required information is provided to the workers, including action planning to balance the workload of human and robot towards minimizing the cycle time, information on the robot status and intensions to facilitate HRC. Online quality inspection (3) prevents the errors propagation to the next process stages.

After the pre-assembly of the sidewalls and the roof frame assembly, a cable-driven robot (4) transports the heavy parts to the assembly location. The robot is responsible for the precise and accurate placement of the frames at the right place without the need for external geometries, fixtures, or jigs. In this stage it is also required that the workers do tedious work overhead to join the frames with each other. Exoskeletons (5) are introduced to reduce the workers' physical strain, and AI algorithms are employed to adjust the level of the exoskeleton support to the current task and the worker's morphology.

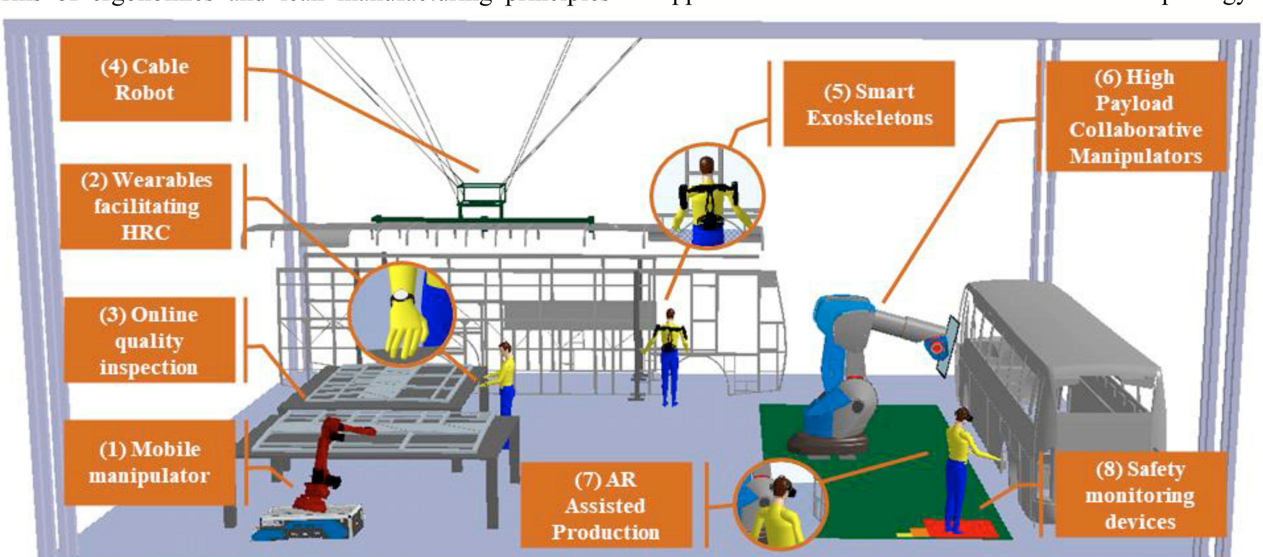

Fig. 3. Case study layout

Finally, doors, windows, electrical equipment etc. should be installed on the painted bus. These tasks are performed concurrently. The windows and doors are heavy parts (weight greater than 25 kg) requiring accurate and precise manipulation. Thus, a high payload collaborative robot (6) is proposed to facilitate their installation and enable the parallel work in the interior of the bus. The robot places glue ensuring a uniform layer of material throughout the adhesive surface. Then it installs the components accurately and applies the correct pressure for the curing thanks to its intrinsic accuracy and precision combined with an external perception system.

Regarding the electrical equipment (interior and exterior), and the internal decoration, human workers are assigned these assembly tasks as they involve deformable components (wires, harnesses, etc.), and high customization. AR glasses (7) can support operators during task execution by providing the current equipment configuration and step-by-step instructions, which before were provided on paper and usually the workers needed to learn the updated each time the process plan by heart. The AR glasses also facilitate the HRC by visualizing robot-related information e.g. robot path and safety zones. The collaborative industrial robot is preferred over a common industrial manipulator albeit the highest cost because the simultaneous processing of the bus interior and exterior is needed. Also, the different bus models differ in length, hence adding fences would result either in space waste (idle area of approximately 7 to 11 m^2) since the greatest possible area should be fenced, or time waste for the fences reconfiguration.

4. RESULTS & DISCUSSION

The introduction of novel solutions can drastically change the shopfloor and the way that production processes can be carried out in the future. However, the adoption of a paradigm relying on Human-Robot Collaboration principles calls for the addressing of several new aspects such as the following:

Safety: The technical development of the functions described in Section 3 presumes the existence of sensors and relevant control schemes to achieve safe, flexible, and accurate operation. The existing safety standards (e.g. ISO/TS 15066, ISO 10218, etc.) foresee the use of multilayer safety systems, including sensors such as safety camera systems (SafetyEYE, https://www.pilz.com) laser scanners (https://www.sick.com), proximity sensors, etc. to track human and obstacles position. Additional control schemes for trajectory planning, navigation of the mobile/cable robots, and safe Human-Robot Interaction and Collaboration also need to be deployed to ensure collision avoidance. Complimentarily, risk assessment studies should be performed to indicate the cell's re-configuration and/or the manufacturing tasks re-design, when necessary.

Autonomy: Uncertainty can be encountered in most of the large part production processes and may come from different sources: Part flexibility, dynamic environment (obstacles, humans etc), accuracy of robotic resources, multitude of production processes, human intervention in the process and so forth. It is therefore imperative that multiple strategies to adapt at different levels are employed. At the resource level multi-sensor monitoring systems (force sensing, depth sensors, visual servoing, etc.) can be used in conjunction with action planning algorithms to allow local adaptation. At the higher levels, methods for generating process plans based on the observation of deviations from the original ones need to be employed and supplemented with automated task assignment and dispatching techniques.

Performance: A set of Key Performance Indicators (KPIs) can be defined to assess and monitor the solution's performance. Typical KPIs involve: (Lindberg *et al.*, 2015; Jetter, Eimecke and Rese, 2018)

- Reduction of cycle time and errors.
- Rejection rate
- Employees' Satisfaction.
- Ergonomics improvement in posture & handling of parts.
- Reduction of non-value adding activities.

These KPIs can be assessed using questionnaires when it comes to qualitative KPIs (operators' opinions), or sensors devices, and historical records for the quantifiable ones.

Results: Implementing the proposed approach is expected to introduce several benefits e.g. cycle time reduction, increase of process repeatability, improvement of the worker's physical and cognitive ergonomics, reduction of fixtures and jigs, optimized task allocation, work balancing, and shorter training periods. This work builds upon the research of Michalos et al., (2018) which dealt with the HRC implementation in manufacturing, and the research of Mourtzis, Zogopoulos and Xanthi (2019) on AR-based tools for operator support. Both research studies reported favorable results, with the first work achieving cycle time reduction in a range of 18%, but also workers' movement improvement up to 40%. In the second work operators report reduction in their mental load.

5. CONCLUSIONS

This paper investigated a new production paradigm for the manufacturing of large-scale parts. The particularities of large parts e.g. geometrical complexity, rigidity and weight were mapped to technological challenges (positioning accuracy, real-time adjustable handling, high-powered manipulation etc.) that need to be met. The analysis of these requirements allowed the identification of a set of key enabling technologies that can address them, shaping a new type of manufacturing environment where multiple types of resources are used. Technologies such as high payload cable driven robots, collaborative manipulators and exoskeletons are already being developed in the PENELOPE EC funded project and will be deployed in domains focusing on large parts production (Oil & Gas, Shipbuilding, Aeronautics, Bus & Coach).

In the following steps, the authors will perform a more detailed study on the implementation of the several resources, emphasizing among others on the safety aspects, and the enabling of seamless HRC. Security by design in terms of access control, authorization, authentication, integrity, and confidentiality assurance will be the basis of the applications which allow the control of devices, as well as access to information. Also, Artificial Intelligence techniques will be investigated for the smart identification of the required level of support provided by the exoskeletons. Finally, since quality control is of primary importance on the manufacturing of large-scale parts, further connection to strategies for Zero Defect Manufacturing is needed. The continuous monitoring of product quality can enable early detection of defects, undertaking corrective actions to eliminate the product defect at first, and minimizing its propagation in the process chain.

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