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An outlook on future hybrid assembly systems - the Sherlock approach

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ABSTRACT

Over the last years both Research and Industry have tried to address the requirement for flexible production by introducing technologies that allow humans and robots to coexist and share production tasks. The focus has been to ensure the safety of humans while interacting with robots. Previous EU funded projects provided proof that humans and robots destiny is collaboration rather than competition. It has been revealed though that Human Robot Collaborative (HRC) applications present drawbacks that limit industrial adoption.

SHERLOCK EU project aims to exploit the lessons learnt and the technical excellence, developing the first high payload collaborative robot (COMAU AURA), dynamically reconfigurable safety monitoring systems and smart Human Robot (HR) interfaces allowing the seamless integration of operators and robots in a common workflow. The aim is to introduce the latest safe robotic technologies including high payload collaborative arms, exoskeletons and mobile manipulators in diverse production environments, enhance them with smart mechatronics and AI based cognition and thus create efficient HRC stations that are designed to be safe and guarantee the acceptance and wellbeing of operators.

1. Introduction

Coexistence of robots and humans in a fenceless workspace poses a fundamental problem of safety. ISO 10218 Part 1, entitled “Safety of Robots and Part 2 on “Safety of Robot Integration” is intended to address workplace safety requirements. Research focused on human-robot collaborative work cells (Tsarouchi et al., 2015) in an attempt to achieve high product customization through flexible systems, which can swiftly switch between products of varying lot sizes (Chryssolouris, 2006).

The co-existence of humans and robots seems a promising solution that allows sharing both workplaces and tasks (Michalos et al., 2014). New projects (LIAA 2020) and products (Universal robots 2020) have been introduced for the exploitation of the flexibility and productivity potential of these hybrid systems. Several approaches have been proposed for human tracking and posture classification using rule based and machine learning techniques (Pintzos et al., 2016). However, the most challenging but important part is to predict the intention of human through analysing his behavior. Nevertheless, the existing approaches are only experimental without producing ready to use results.

Several research studies have been done in implementing human robot interaction interfaces in terms of efficient communication channels between the robot and the worker. Approaches already developed involve, among others, the utilization of force sensors or joysticks attached on the robot, gesture recognition (Makris et al., 2017) and natural speech (Zuo et al., 2010). However, the majority of the Human Robot Interaction (HRI) robotic systems available at the market and applied on industry are relatively smaller robots with maximum payload of 10 kg and high-payload applications involve new challenges.

One of the latest trends in human operator support provision technologies is the use of wearable technologies that can provide a number of feedbacks in the manufacturing industry (Wang et al., 2018). Such technologies are based on wirelessly connected wearable devices such as Augmented Reality (AR) glasses, smartwatches etc. that can retrieve real time data concerning the shopfloor status. Nevertheless, apart from some small-scale experimental installations where humans have a more active role, many of the above applications have not reached the production site.

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Also, the capabilities of smartwatches have been slightly exploited (Gkournelos et al., 2018).

On the other hand, robot programming systems applied in the industry are still characterized by proprietary and low-level robot motion-oriented programming (largely based on TP programming and TCP/IP interfaces). Despite intensive research of advanced programming concepts and the actual low-level robot-motion oriented programming, specific robot languages still dominate industrial robot sectors (Biggs and Macdonald, 2003). The task programming greatly simplifies program design of complex assembly operations to be realized by composite robotic systems such as dual-arm robots.

To achieve a seamless coexistence of robots and humans inside the workcell, robots should be able to detect and recognize objects, accurately estimate their pose, and read the 3D structure of its environment. Vision systems are commonly used but no general solution exists. In terms of Perception, the industrial applications require to manipulate parts with no or bad texturing, complex shapes, metallic reflections etc. So common 2D image analysis and classification using deep learning cannot be used. 3D vision is usually required. Most methods align a precise model of each object with 2D image (Sepp et al., 2006) or 3D range data (Hillenbrand, 2008) (eigen-images), feature-based (sift-features, surf-features), descriptor-based (wavelets) or color information (Chang and Krumm, 1999). Color and brightness information is usually complemented with depth information (Hirschmüller, 2005). Time-of-flight cameras gain popularity being able to provide depth information also in homogeneous areas. Furthermore, each application has its own parts and features. No database with industrial parts currently exist to train a neural network on this kind of 3D parts. The current use of vision in industry involves 2D sensing using cameras (e.g. Cognex) to perform a fine pose adjustment or the calibration of a zone before performing the process. 3D vision, pointcloud registration for pose estimation is also sometimes used in advanced applications, but it still requires lots of expert tuning and programming.

HRC increases the possibilities of direct physical contact either due to the intrinsic of the operations or behavior of the operator. In addition to this, bad design of HRC cells or bad selection of components, such as grippers that do not comply with safety requirements (unprotected), can lead to inefficient applications and production outputs. For this reason, several technologies to identify and avoid unintended physical contacts have been published. However, current formal methods for safety analysis of HRC do not recognize the operators as proactive factors and thus the research is strongly focused on formal analysis of robots' behavior, which is verified by model checking techniques. These techniques are suitable for checking the correctness of the robots' components but under some limitations: is quite impossible to have a complete formal deterministic description of the surrounding physical world.

On the other hand, formal standards for industrial robotics are devoted to functional performance and safety with any consideration of human requirements almost exclusively confined to physical ergonomic issues. Operators' psychological safety and ethical issues have not been before highly concerned, because the robots in factories remained segregated, away from human contact, behind physical fencing. Also, the need for advanced manufacturing training methods is not so high for such cases, since the humans don't collaborate directly with the robot (Mital et al., 1999). Industrial applications of HRC only started being addressed in international standards in the past decade in some clauses of ISO 10,218–1 / −2. In 2015 ISO published TS 15,066 as an interim measure to address the growing need for HRC standards before the 10,218 revision. The focus of these standards remains on technical safety and is not expected to venture in psychological aspects.

Exoskeleton technologies bring new capabilities and improve endurance and safety in industrial settings. They are designed to increase industrial productivity and can prevent common workplace injuries. Thus, work has been done defining the necessary framework for their integration in production lines (Karvouniari et al., 2018). Despite that, their communication with the rest of the industrial elements and adaptation based on the working conditions and tasks being executed is still a challenge and has to be addressed.

This paper discusses the concept of the EC project SHERLOCK (www.sherlock-project.eu) towards enabling seamless and safe human-centered robotic applications for novel collaborative workplaces, trying to address the aforementioned bottlenecks.

In Section 2 the proposed approach is detailed, while in Section 3 four reference use cases where the proposed approach is applied are analyzed. In Section 4 the main Key Performance Indications (KPIs) that will allow the evaluation of the effectiveness of the proposed approach are presented. Finally, Section 5 concludes the work presented and includes information about future work.

2. Approach

SHERLOCK aims to address the bottlenecks in hybrid human-robot collaborative cells by introducing the latest safe robotic technologies including high payload collaborative arms, exoskeletons and mobile manipulators in diverse production environments, enhancing them with smart mechatronics and AI based cognition, creating efficient HRC stations that are designed to be safe and guarantee the acceptance and wellbeing of operators. More details on the technologies introduced will be presented in the following sub-sections.

2.1. Soft robotics devices for collaborative production station

At the core of the SHERLOCK project is the Soft Robotics Collaborative Production Station similar with enhanced robotics resources which are incorporating new technologies implementing safety and interaction combined with high payload and mobility. At the center of the collaborative station are the soft robotic devices that will act as partners to the human operators. SHERLOCK will adopt, enhance and customize soft robot technologies for different production scenarios. More specifically both active and passive collaboration among robots and operators will be enabled through: a) the introduction of the first High payload collaborative manipulators (COMAU AURA) (COMAU AURA 2020), b) Low payload collaborative manipulator, c) Exoskeleton devices and d) Collaborative mobile dual-arm robot, depicted in Fig. 1. The robotic resources mentioned above will be developed and enhanced within the project.

2.2. Novel human – centered interaction & programming mechanisms

The quality of interaction is of primary importance to ensure human acceptance. In the past projects a lot of steps towards this direction have been made, introducing innovative technologies using wearable devices and sensors that enable the intuitive interaction between human and robot. Nevertheless, the discussed interaction strategy had a generic approach without being designed and implemented in such way to adapt to the specific needs of the human operators. To take it to the next level, SHERLOCK will revisit the HR interfaces following a human-centered approach to select and optimize the ones that result in a smoother collaboration. The target is to offer interaction means (s/w and h/w) that adapt to human needs and particularities and account for the requirements of the tasks. SHERLOCK will use the same interfaces to offer operator the ability to intervene and change/teach behavior eventually

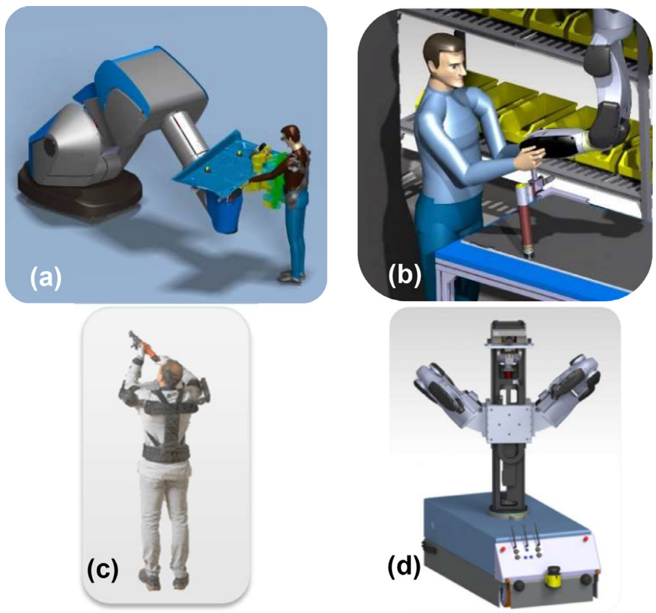

Fig. 1. SHERLOCK soft robotics – a) High payload collaborative manipulator, b) Low payload collaborative manipulator, c) Enhanced exoskeleton device, d) Collaborative mobile dual-arm robot.

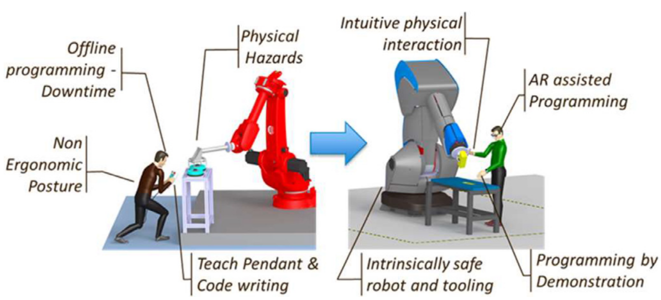

Fig. 2. Conventional vs SHERLOCK based programming and interaction.

making a shift from the fixed operation to a more reconfigurable paradigm able to cope with small batches, a concept which will be also achieved by teaching by demonstration and interactive learning of robot skills (Fig. 2).

2.3. AI enabled cognition for autonomous HR collaborative applications

Current robotics applications can execute strictly predefined workflows and are not able to dynamically adjust their tasks where non-deterministic events take place such as in the case of human intervention. It would be thus impossible to predict and preprogram every possible unexpected occurrence. SHERLOCK recognizes the fact that genuine collaboration may only be achieved when both collaborating entities are aware of the working environment and the dynamic behavior of other resources and are able to analyze and reason upon it. While it may come more natural for a human to perform so, robots need to be better equipped for the job. Thus, AI based tools that will facilitate the autonomous HR collaboration will be developed, such as: i) process perception module able to identify the actions being performed by human operators, ii) workspace monitoring module able to identify the presence of human operators and obstacles inside the workplace feeding the robot motion planners with valuable data to avoid possible collisions while generating the robot path, iii) shopfloor digital representation module, being an one to one replica of the real one, updated with data deriving from distributed sensor network installed inside the workcell, iv) task and action planner able balance the workload between robotic resources and human operators inside the workcell, identifying the best course of actions, v) autonomous learning strategies for robot behavior adjustment to human needs (Fig. 3).

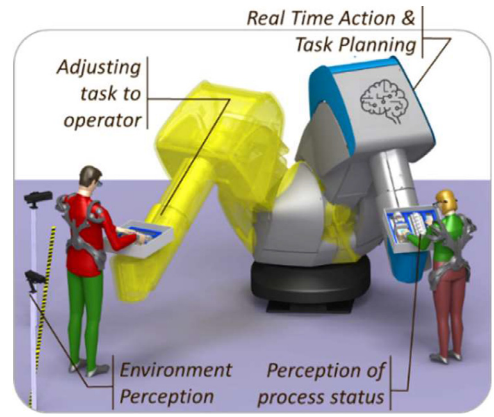

Fig. 3. AI enhanced modules.

Fig. 4. Automated Risk Assessment Design Modules.

2.4. Design and certification of safe HRC applications

SHERLOCK is human-centric and this means that safety and wellbeing of operators are the highest priority. In the pursuit of seamless collaboration and high performing HR systems, new directions need to be considered such as use of robust methods to ensure safety in a dynamically changing environment and the provision of training methods especially designed for HRC operations - allowing operators to become familiar and trusting in the use of robots. SHERLOCK wants to encapsulate knowledge from the existing applicable laws and standards into software design modules that will automatically evaluate HRC cells against the requirements for safety, using VR and AR technology (Fig. 4). The target is to include human aspects/safety systematically in the design which currently follows the traditional automation perspective where humans are not considered to collaborate with industrial robots. Moreover, to increase the performance of HRC tasks and actions, SHERLOCK develops a novel on-line monitoring system based on formal methods, safeguarding operators in HRC environments without compromising the overall interaction efficiency (Fig. 5).

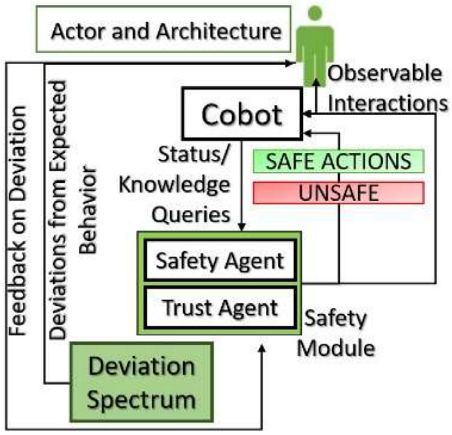

Fig. 5. SHERLOCK Online safety assessment modules.

3. Use cases

3.1. Elevators cabin assembly

Current State: This use case aims to take advantage of the SHERLOCK developments for improving the ergonomy of the workers during the production process, given special emphasis to operators with special restrictions who face more challenges against the required assembly tasks. The pilot focuses on the workstation where the cab door panel hangers are pre-assembled prior to being assembled on the cab door. Different types of hangers, variable in size (300 × 650mmm, 400 × 800 mm), weight (from 11 to 25 kg) and number of components (10 to 12) are encountered. Operators have to lift the metal hangers, move them around the shopfloor and assemble the various smaller components. Two side accessibility is required and thus the main panel must be repositioned a lot of times during a shift. Operators are facing several ergonomic issues as they are requested to manipulate heavy load while the nature of the tasks being executed prohibits the employment of operators with restrictions

Future vision: SHERLOCK promotes the use of a high payload collaborative robotic solution to handle the heavy parts, moving, rotating and presenting them to the operator in the most convenient way to perform the assembly. This signifies a paradigm shift from the case where the part is static, and the operator moves and bends around it to an instance where the part is moved as per his/her desire and comfort reducing non-value-added activities by 25%. AI based perception systems using a distributed sensors network will ensure a safe interaction, while control modules will ensure correct assembly by verifying the sequence of operations being performed by the human operator (Andrianakos et al., 2019). At the same time support is provided to the operator in the form of AR visualizations indicating the correct part (screw type, diameter etc.) and the target positioning on the main part. The SHERLOCK system predicts safety violations caused by the operator or the cobot and applies formal methods and machine learning to learn the operators' preferences and reduce false alarms and for preserving the current cycle (Fig. 6).

3.2. Industrial modules assembly

Current State: This use case involves the production of large aluminum panels used as outer covers for machines producing microchips. In the current assembly workstation the main stakeholder is the operator. Two operators are working simultaneously. Each operator is responsible to complete in detail the assembly of each panel and place it in the area with the complete products. In addition, the operator is responsible to retrieve the supplies (that is, parts like screws, hangers, handle etc.) required for the current assembly phase. The panel is lightweight (~5 kg), so it can be effortlessly manipulated by the human operator. The main challenge though is that a large number of panel variants is being assembled per shift, while the assembly involves a lot of repetitive actions (such as riveting) and installation of a large quantity of smaller parts on top of the large aluminum panel. This causes mental fatigue to the operator who is then prone to assembly errors. Moreover, the monotonous repetitive actions that the operator needs to perform lead to a feeling of discomfort.

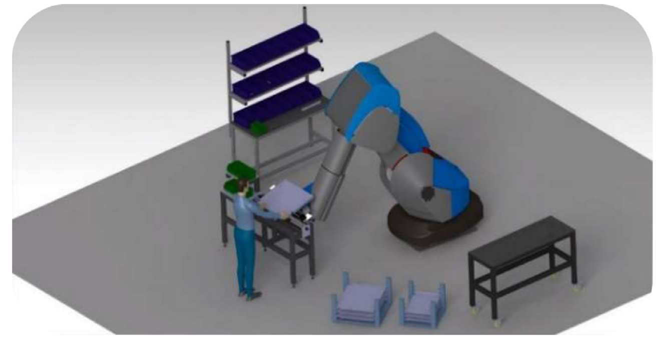

Fig. 6. Elevators cabin assembly - SHERLOCK vision.

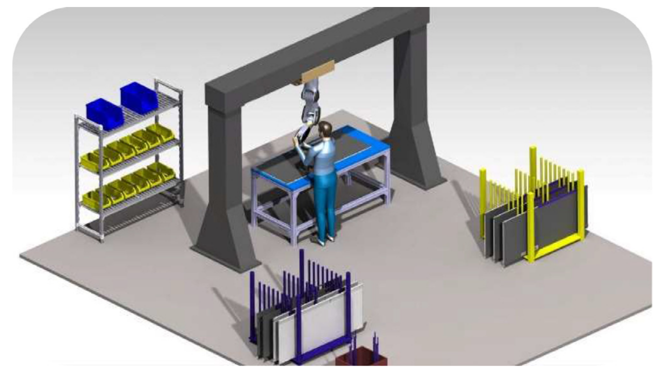

Fig. 7. Industrial modules assembly – SHERLOCK vision.

Future vision: Collaborative robots would eliminate the room for human error, creating a much safer environment for the humans to work. As the requirements for high payload manipulators are not very high, the application will benefit from the utilization of a low payload collaborative manipulator assisting the human operator in assembling the panel together. The robot will handle the repetitive actions (such as riveting) while human operator will focus on the actions that will benefit from human dexterity. Moreover, SHERLOCK solutions in HR interaction and robot cognition will ensure a seamless and safe interaction among the resources, while workload among humans and robot will be balanced via the aid of AI based task and action planning software. Given the high production rate to be achieved it is critical that the human and robot can communicate and execute their tasks in harmony (fluent interaction). Moreover, online safety assessment methods will ensure the safety of the operator, while not sacrifice production speed. The envisaged production station is shown in Fig. 7.

3.3. Exoskeleton assisted machine building

Current State: The third pilot case focuses on mechanical assembly, inspection and service maintenance operations of large machine tools. These operations are currently performed by human operators manually, with complete lack of automated procedures,

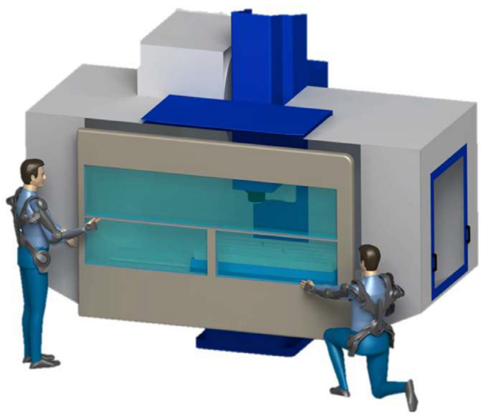

Fig. 8. Exoskeleton assisted machine building – SHERLOCK vision.

since the available working area is limited and the whole process is characterized by a high degree of customization. Operators need to carry heavy parts, lift them up-high and perform the assembly of the machine tools, in narrow areas. Also, today's market needs, require such machines to operate 24/7 and thus be in a perfect condition and cover any production peaks that may occur. For this reason, their installation and maintenance are quite stressful tasks, since the operators need to respond to high time pressure duties.

Future vision: SHERLOCK foresees the introduction of soft robotic systems and the necessary algorithms to support the operators in their strenuous tasks both physically and mentally. More specifically, semi-active exoskeleton devices will support the human operators carrying the heavy parts during their shift in a non-intrusive way. This collaboration promotes work environments where robots assist workers as members of the same team, helping them mount the machine parts when in uncomfortable or dangerous positions, during heavy load handling. The exoskeletons will be actively reconfigured depending on the task progress which is monitored by the AI enabled perception modules which collect information from the exoskeleton and the wearable devices on the human. The AR and smartwatch interface allow the operator to change the behavior of the exoskeleton at will and to request support when performing the assembly task in the form of instructions, drawings or overlaid AR models (Fig. 8).

3.4. Aeronautics components production

Current State: The fourth pilot case focuses on co-manipulation and positioning of large composite aeronautics parts on tooling used for accurate processes (edge milling and finishing or Non-destructive testing). Today, the carbon fiber parts are not heavy but their large size (up to 7 m) and the distance to be covered between working areas prohibit a manipulation by a single person. Two workers are needed for its placement and the rest of the tools are positioned by one worker. Only one operator is bringing added value to the positioning process while the other workers only help to follow the leader and sustain the part's weight. There is an evident collaboration between the operators to perform the task, using force, vision and voice modalities for coordination.

Future vision: SHERLOCK will introduce a collaborative mobile dual-arm manipulator able to hold the part, move along the workshop in tandem with the operator, and cooperate with him to accurately position the part on the tooling. This seamless coordination between the robot and the operator will be achieved by multiple cascaded control loop: a physical interaction control using dual-arm impedance control, combined with the mobility of the mobile base, and the human guidance perceived through vision and voice. The part to be manipulated is flexible due to its dimensions and the robot cannot just follow the operator: it must learn its own positioning skill, using 3D vision for the tooling detection, and interactively learn a funnel of trajectories to perform its own dual-arm manipulation and installation, in cooperation / synchronization with the operator. Given the number of parts and process variability robot skills teaching will be a key feature (Fig. 9).

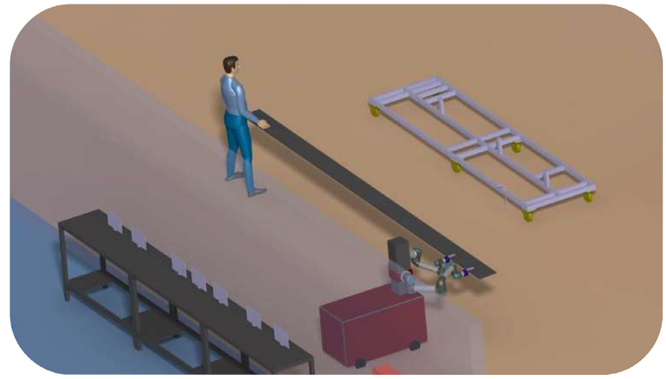

Fig. 9. Aeronautics component s production – SHERLOCK vision.

4. Results & discussion

Although the use cases presented in Section 3 seem to diverse quite a lot, common Key Performance Indicators (KPIs) can be extracted that will allow to evaluate of the benefits of the proposed approach. The main KPIs are summarized below:

- Ergonomics improvement in posture & handling of parts
- Maximum weight of part to be manipulated by the operator: target is to reduce the maximum weight manipulated by the operator and in cases this is not possible, the goal is to reduce the maximum weight felt.
- Employment of operators with special restrictions
- Time to introduce a new product variant in the assembly station: reduction of the amount of time required, achieved by the innovative programming techniques.
- Cycle time: improvement of cycle time compared to manual execution of the various operations.
- Product quality: reduction of assembly errors by the operators
- Return of investment: referring to the relation of profits against the capital invested.
- Reduction of non-value adding activities
- Number of operators required in the production cell: since some tasks can be executed by the robotic resources introduced, the number of operators who are working at the same production cell can be reduced and thus the extra operators can work at another workstation, increasing productivity of the factory.

Conclusion & future work

This paper discussed the requirements and challenges for the creation of flexible and safe human-robot collaborative workplaces that allow the seamless interaction and collaboration among the resources. The enabling technologies were described as well as four indicative use cases where they will be applied, along with the main KPIs that will enable the evaluation of the proposed approach. The technologies described in Section 2 are currently being implemented under the SHERLOCK EC funded project and will be integrated in several pilots from the elevators, industrial modules, heavy machinery building and aeronautics production sectors.

Future work will focus on the development of the technologies discussed in Section 2, their optimization and their integration under a common production station. Moreover, future work will focus on the deployment of the developed production station at industrial environment. This will allow to accurately measure the performance of the system as a whole and highlight bottlenecks in human-robot collaboration, safety, efficiency, interaction, performance, as well as operator acceptance of such technologies.

Declaration of Competing Interests

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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