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ARCHITECTURE OF HUMAN-ROBOT COLLABORATION IN MANUFACTURING INDUSTRIES

Abstract: *The fourth industrial revolution (I4.0) implies more collaborative and connected manufacturing. Industry 4.0 and smart manufacturing integrate human and intelligent devices to enhance workplace safety in a collaborative industrial environment (Safety 4.0). Collaborative robots (or cobots) have been developed with intuitive interfaces that support human operators in the physical workload of manufacturing tasks, such as handling hazardous materials or executing repetitive and monotonous actions with high reliability, such as assembly activities. However, the deployment of cobots must include application safety criteria to be taken into account in order to improve their interaction with operators. In this way, Human-robot collaboration (HRC) is being adopted in the smart manufacturing industry as a solution that mixes, within a shared workspace, the dexterity and cognitive faculties of human operators and the accuracy and repeatability skills of robots, guaranteeing no-danger conditions and absence of collision during this type of collaboration. The aim of this paper is to propose human-robot collaboration architecture and show how it will be possible to improve workers' safety through the implementation of the proposed architecture. Intelligent devices are integrated into human-robot workstations in order to protect the operator from hazards, injuries and occupational diseases. The proposed paper highlights safety guidelines regarding HRC and their application using smart equipment, such as sensors, computer vision systems, and so on. Overall, interaction with different degrees of collaboration and technologies increases not only the flexibility but also the complexity of the system. Therefore, this paper also focuses on identifying the main safety requirements in human-robot collaborative systems design*

Key words:architecture of human-robot collaboration,collaborative robot, human-robot collaboration, Industry 4.0, Safety 4.0, Occupational safety and health

INTRODUCTION

Due to increasing competition in the global market and in order to respond to changes in customer requirements, organizations tend to introduce self-configurable and smart solutions in assembly production processes to ensure more efficient and ergonomic performance of work activities. Advanced digitalization has led to the fourth industrial revolution (or I4.0), where physical production is connected with smart digital technology. Its goal is to allow manufacturers to meet the ever-changing demand more efficiently and improve production processes using contemporary advanced technologies. Industry 4.0 denotes an approach to enabling the next generation of manufacturing (Hermann et al., 2016) and advocates the increased use of sensors, information and communication technologies, and advanced automation throughout factory facilities, promising shorter development times, increased customization, greater flexibility, and improved resource efficiency (Kadir et al., 2018). Moreover, I4.0 will bring new paradigm shifts, which will have a positive impact on the management of occupational health and safety (OHS).

Automation and the application of collaborative robots contribute to enhanced efficiency and reliability of many assembly tasks that were previously performed manually by humans. On the other hand, the introduction of innovative technologies complicates manufacturing systems and increases the need for safety requirements (Tan et al., 2019).

Although traditional industrial robots were designed for performing highly repetitive and difficult tasks, their accuracy was low and they were not easy to program. Moreover, in complex assembly systems, their deployment might be a hazard for the operator and the other entities.

Collaborative robots (cobots) are designed to work, interact, and collaborate with humans (Kadir et al., 2018) in a common workspace. In this regard, their deployment is also changing the role played by humans in the workplace (Cherubini et al., 2016). In hybrid assembly systems, the robot holds the part for the worker who can adjust its position and mount it.

The main difference between cobots and traditional industrial robots is that cobots are designed to allow physical interaction with the operator in hybrid and fenceless work cells without the necessity of isolating the robot workspace. During Human-Robot Collaboration (HRC) within a shared workspace, the dexterity and cognitive faculties of human operators and the accuracy and repeatability skills of robots are combined, guaranteeing no-danger conditions.

On the other hand, the deployment of cobots requires safety criteria to be taken into account in order to improve their interaction with operators respecting the fact that interaction with different degrees of collaboration and technologies increases not only the flexibility but also the complexity of the system. The aim of this paper is to propose a human-robot architecture based on which workers' safety and health will be improved. The architecture involves a collaborative robot, a Poka-Yoke system, an audio 5.0 system, an EEG device, and a touch-screen PC and industrial computer. The paper also focuses on identifying the main safety requirements in human-robot collaborative systems design.

HUMAN-ROBOT COLLABORATION

The application of advanced technologies (sensors, actuators, cameras, computer vision systems, etc.) enables the automation of the production process and delivery of the final product with minimal human intervention. It is especially important to apply automation in production processes that are not ergonomically suitable for humans, where workers are highly exposed to harmful and dangerous substances and where exceptional precision, which humans are not capable of achieving, is necessary. These technologies are applied to conduct real-time information collection, processing, and feedback control of the monitoring of workers' posture, health status, etc.

In I4.0, cyber-physical systems (CPSs) represent networks composed of physical objects and resources. This interconnectivity enables entities to communicate and cooperate with their environment and make decisions independently in the intelligent production process (Weiss et al., 2021).

In CPS, a collaborative robot (or cobot) is an important actor. Cobots are a particular kind of industrial robots, which are able to physically and safely interact with humans in a shared and fenceless workspace. Cobots help operators with non-ergonomic, repetitive, uncomfortable and dangerous operations. The main features that distinguish a cobot from a traditional factory robot include improved safety features for working near the operator and simplified programming to allow for flexible application, enabling simple deployment and redeployment within a factory (Faccio et al., 2019).

In particular, HRC is the most advanced application of Human-Robot Interaction (HRI) in industrial settings, since it involves a simultaneous sharing of tasks and workspaces between the operator and the robot's system (Gualtieri et al., 2022).

Human-robot cooperation has been the focus of a large number of scientific papers in recent years (Mathesonet al., 2019). HRC implies cooperation between a purposely designed robot system and an operator within a collaborative workspace (ISO, 2011a). These hybrid systems have to be selected and implemented depending on the task goal and the level of interaction (Weiss et al., 2021). Collaborative industrial robots perform tasks in collaboration with workers during production operations in a collaborative workspace (IFR, 2020; ISO 2016). Furthermore, they support workers with both physical and cognitive tasks. For example, a collaborative robot and an operator jointly perform assembly activities in such a way that the robot moves its hand into a specified position and orientation and then waits until the human places the object between the fingers of the gripper. When the robot detects that an object has been placed in its hand, it attempts to grasp the object. The same case has been applied previously for handing over an object from a robot to a human or during the performance of an assembling task (Edsinger and Kemp, 2007). The human operator mainly monitors the tasks and the operator's presence in the tasks, which is not continuous. The robots are designed in such a way that, unlike humans, they can work continuously without interruption and produce high-quality parts, while humans become tired after a certain time.

In an HRC environment, the abilities of the human and the robot are combined and integrated (Gervasi et al., 2020). Hence, the introduction of robots has a role to increase the efficiency and productivity of the production process. On the other hand, the role of human workers is mostly to compensate for the technological limitations and act as decision-makers for improved production planning and control with the support of these advanced systems (Nelles et al., 2016).

The interaction between humans and robots is achieved via voice command, gesture recognition, etc. Also, direct collaboration between the human and the robot can be achieved by using force control (Vysocky and Novak, 2016). Using EEG signals to connect a human with a collaborative robot and controlling humanoid robots using human EEG signals was the focus of a numerous research papers in the previous period (Wang and Chang, 2020, Weiss et al., 2021). Some research papers (Krger and Surdilovic, 2008; Yu, 2019) point out the possibility of using EEG signals to guide a robot in a collaborative environment. Communicating with a robot through EEG signals provides many benefits: the possibility to control a robot and execute collaborative activities and present a supporting communication with the robot in addition to other channels, such as voice, gesture, etc.

The main goal of HRC is to improve workplace safety and ergonomics, productivity, flexibility and effectiveness. Many manufacturers are eager to adopt HRC technology to enhance the effectiveness and flexibility of their production. The human operator is able to operate variant productions while the work-ability can be restricted by ergonomic factors and hence influence the accuracy and production volume (KUKA, 2016).

A research study on HRC has presented a human-centric design (HCD) approach, which is more focused on applying safety and ergonomics knowledge and techniques (ISO 9241-210: 2010). Therefore, such an approach aims to improve human well-being, together with satisfaction and accessibility, while preventing the potential side effects on human health, safety, and performance (Gualtieri et al., 2020; Yu, 2019).To build up production systems with direct HRC, cobots with integrated safety features are needed.

SAFETY REQUIREMENTS IN THE DESIGN OF A HRC

Traditional industrial robots can handle high repetitive and payload tasks (ABBRobotics, 2019). However, in complex assembly systems, this is too expensive to achieve and dangerous to human operators (Hagele et al., 2002). On the other hand, a collaborative robot is equipped with safety components. During HRC, sensors built into the cobot detect the presence of a human in the collaborative workspace and thus ensure the safe performance of a manual operation and the safety of humans and the surrounding work environment. To avoid collision in a shared workplace, the position of the operator has to be known in real-time (Ahmad and Plapper, 2015). Also, the moving trajectory of the operator and speed of movement has to be assessed continuously.

During the collaborative task, the robot relates to the operator through intuitive interfaces. However, the robot’s trajectory might be unsafe for the operator and the surrounding work environment. Also, unwanted and unexpected contact between the human and the robotic system may cause injuries and therefore limit the potential for collaboration. Nowadays, there is a lack of simple and practical tools for helping system designers overcome such limiting conditions (Gualtieri et al., 2022). Consequently, safety requirements and measures for collaborative robotics must be studied and harmonized (Gualtieri et al., 2021).

In 2016, a new ISO technical report, ISO TS 15066 (ISO 2016), was published in order to help production technicians and safety experts with the development of safely shared workspaces and with the risk assessment process. This report specifies in greater detail the previous safety requirements for industrial robots included in ISO 10218 parts 1 and 2 (ISO 2011a, b). It also includes requirements and suggestions for collaborative applications.

The ISO TS 15066 standard (ISO 2016) introduces four methods for safe HRC:

a. Safety-rated monitored stop (SRMS): the robot’s motion is stopped when an operator enters the collaborative workspace. SRMS represents the simplest type of collaboration. There are applications where the robot shares a part or all of its workspace with operating staff. In the shared area, the robot and the operator can work, but not at the same time.
b. Hand guiding (HG): the operator can fully control the robot's motion through direct physical interaction. The robot learns and repeats the motion without the interaction of the operator. In this case, the robotic task is manually guided by the operator at a certain safe velocity by moving the arm through a direct input device at or near the end-effector.
   For improving workplace safety and avoiding a collision, there is an enable button in the grabbing area, because the robot can only move if the button is pressed, otherwise, it will stop.
   The robot has to be equipped with a measurement device to monitor the impact load. Some robots have sensitive elements embedded directly in their joints. These sensors measure and evaluate the load and control the compliance of the robot.
   HG is used in case of a coordinated motion of semi-automated operations or during the programming of the robot. Positions of the desired trajectory are learned according to the guidance of the manipulator by the operator (Vysocky and Novak, 2016).
   Hand guiding is applied in limited or small-batch production as a robotic lift assist. The robot can achieve better ergonomics when carrying heavy objects. In that case, operators only need to deal with a small guiding force.
c. Speed and separation monitoring (SSM): the control system of the robot is actively monitored by the relative speed and distance between the robot and the operator. The operator has access to the shared workspace while the robot is running, but as the operator gets closer to the robot, its speed reduces accordingly. The distance between the robot and the operator can be monitored with lasers. Also, lasers or cameras may monitor the operator’s path.
   This method is designed to prevent unexpected contact between the operator and the collaborative

robot by reducing the probability to fit the safety limits.

Appropriate sensors detect the worker in the collaborative workspace. Furthermore, this information must be used by the robot controller so that the robot's speed is adjusted to avoid moving contact with the worker. With SSM, the workspace of the robot cell is divided into several areas. These are inspected with scanners or a vision system. In areas out of the reach of the manipulator, where the operator does not come into contact with the robot but can be endangered by a dropped manipulated object, the robot is slowed down to a safe speed. The speed and position of the robot are continually monitored (Vysocky and Novak, 2016).

d. Power and force limiting (PFL): physical contact between the robot system and the human operator can take place either intentionally or unintentionally. The motion parameters of the robot are monitored with high precision, and even the slightest deviation can be detected. The high precision encoder and high resolution allow the robot to accurately monitor its own speed and position.

The robot can recognize the impact of obstacles and analyze and react to them in a very short time. After a collision, the robot can stop immediately or it can move in the opposite direction, minimizing the impact. Also, the robot can safely react after collisions and readjust its position without interfering with the operator or other systems working in close proximity.

The PFL method is applied in conditions that require frequent operator presence.

The first three collaborative modalities are adopted without the necessity of using an industrial robot that is specifically designed for collaborative applications. The "power and force limiting" is the only collaborative operation that requires robot systems specifically designed for this particular type of operation (ISO 2016).

PROPOSED HRC ARCHITECTURE

The proposed HRC architecture implies a heterogeneous system, which is deployed in the hybrid human-robot workstation for the conduction of neuroergonomics experiments. Computer systems, interfaces and sensors are integrated into that architecture in order to analyze the workplace condition, habits, and behaviour of operators in the workplace. The proposed setup includes (Savković et al., 2022)

- a collaborative robot;
- a Poka-Yoke system;
- an audio 5.0 system;
- an EEG device;
- a touchscreen PC; and
- a computer.

The proposed framework was inspired by the approach presented in the technical reports by different authors (Arents et al., 2021).

The proposed architecture for an adaptive and modular workstation, in which the operator may work in close proximity to the robot, is presented in Figure 1.

In this collaborative environment, the operator and the collaborative robot perform activities together (Savković et al., 2022). The robot is the primary task performer. Unlike classic robots, cobots have built-in sensors that allow them to recognize and analyze workers' intentions and adapt their activities to the capabilities of the workers (Bonini et al., 2015) by monitoring the physical and cognitive workload of the workers.

This collaborative robot meets the requirements of international robot standards ISO 10218-1 and ISO/TS15066. The specific nature of the robot is reflected in the fact that it is more accurate, easier to reprogram, and can communicate securely with operators (Cherubini et al., 2016). Furthermore, it has no sharp edges, and all the dangerous parts are round and smooth. Despite the benefits of collaboration with the robot, the machine may be a source of potential damage in the workplace. In this regard, ISO standards (also called harmonized standards) must be designed to guarantee a safer collaborative environment.

Some of the standard components of this collaborative robot include

- a robotic arm;
- a controller;
- a power cord;
- a safety switch; and
- Memory.

Figure 2 shows the components required for the operation of the collaborative robot. In addition to the robot arm, the controller, and the power cable, the components required for the operation of the robot include a computer (13) with appropriate software, a panic-emergency button (3), a power supply for an auxiliary safety device (8), a switch for setting the operating mode (1), a grounding cable (7), and a manipulator/gripper (12).

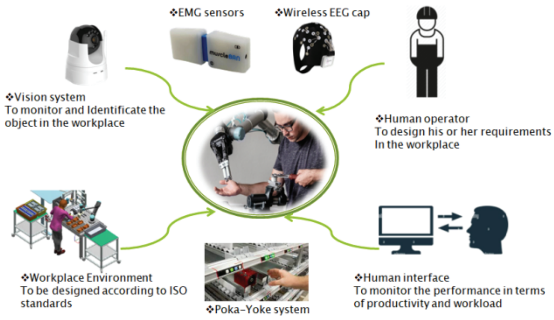

Figure 1: Proposed *HRC architecture*

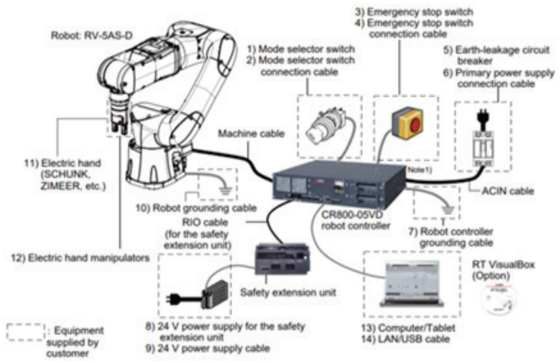

Figure 2. *Basic components necessary for collaborative robot operation*

The robot has buttons on the operating panel that corresponds to specific functions, as shown in Table 1 and Figure 3.
Integrated safety elements include a robot controller with safety-rated motion supervision, a sensor system to monitor the collaborative workspace, and grippers with pressure control.

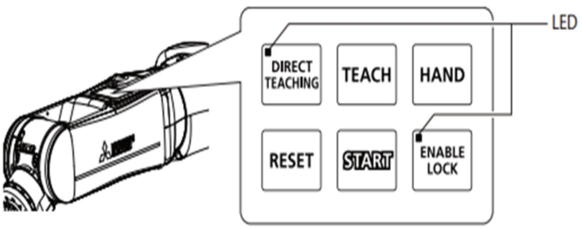

Figure 3. *Buttons to control the collaborative robot (Mitsubishi Electric)*

Table 1. *Description of buttons on the collaborative robot*

BUTTONS	FUNCTION
DIRECT TEACHING	It allows manual programming of the robot
TEACH	For learning positions where appropriate software is required
HAND	Function related to gripper opening and closing
RESET	Reset after errors
START	After stopping the robot, it is necessary to press the START button
ENABLE LOCK	This feature prevents the robot from being controlled by other devices

The position controller ensures that the current position always matches the set point on the commanded motion with a minimum possible difference. The robot's position is controlled by actuators in order to readjust its motion after a collision or deviation. The impedance control is used to measure the force between the manipulator and the human.
The control system supervises the activities of the robot and also sets the limit for the robot to avoid collisions in the environment. This part can manage the position, motion and force, as well as the dynamic effects.
The LED status indicator provides visual assistance when controlling the robot, whereby it immediately warns whether there is a problem or an error during the operation of the robot, which operating mode it is currently in, and at what speed it is operating.
The robot's vision system involves a camera and a software toolkit to enable the robot to obtain data and execute physical response actions. Using the vision system, the collaborative robot will be able to detect and recognize a human face and load a free human hand and any object carried by a human hand. The visual monitoring system involves the use of the camera to track the operator in the human-robot interaction process and achieves visual monitoring through the operator's eye gaze and head position (Song et al., 2001). Collisions can also be predicted by the visual system. In case of a collision, the robot is equipped with passive protection components designed to minimize damage.
Authors used RT Toolbox3 to manage the collaborative robot. This PC software supports everything, from system startup to debugging, simulation, maintenance and operation (Wang and Chang, 2020).
An integrated sensors system ensures the safety of the operator. The sensors, as the most important safety component of the HRC system, are used for internal feedback control and monitoring of external interactions with the environment. Sensors are used for physiological and visual monitoring of human poses and for the behaviour monitoring system during HRC (Bonarini, 2020). The sensors include proprioceptive sensors (position sensors, velocity sensors) and exteroceptive sensors (proximity sensors, range sensors, vision sensors). Proprioceptive sensors focus on the measurement of the internal states of the manipulator – encoders and resolvers are mostly used for the value of the joint position, tachometer for measuring the joint velocity, and force sensors for measuring the force of the end-effector (cobot). On the other hand, the exteroceptive sensors acquire information from the cobot's environment (Soter et al., 2018). The force sensor helps the robot react to the motion of the human hand during task performance.
Physiological monitoring systems comprise wearable devices monitoring the vital operator's parameters during HRC. In this case, the cobot receives these inputs and reacts according to the operator's health status. In this regard, innovative wearable and wireless devices such as EEG, EMG and heart rate sensors are

deployed in HRC in order to enable physiological interaction between the worker and the robot (Villani et al., 2018).

A PC is integrated into this collaborative workstation to monitor and control the performance of various activities/tasks and to allow process visualization. A touchscreen PC is connected to the system for task symbol definition and application of a sound signal. An audio 5.0 system serves to emulate the sounds of the workplace environment.

A Poka-Yoke system enables the prevention of errors and defects due to a drop in attention and concentration in such a way that guides operators through the assembling process and indicates which part they should take at which moment.

An EEG system is used to perform neuroergonomics experiments during HRC in order to measure the subject's neural activity and determine when there is a drop in attention and concentration.

CONCLUSION

Human-robot collaboration is the main aspect of Industry 4.0. The main reason for the introduction of cobots in the production process is to improve worker safety and health and improve the quality of finished products. Collaborative robots offer flexibility and precision for manual tasks that have previously been difficult to automate. Collaborative robots provide new automation opportunities in areas with a high degree of manual labour. During HRC, collaborative robots perform activities with workers and they are especially beneficial because they protect the workers performing repetitive activities in a dangerous environment.

This research paper presented the human-robot collaboration architecture and showed how to improve workers' safety through the implementation of the proposed architecture. In human-robot workstations, intelligent devices (sensors, computer vision systems, and so on) are integrated in order to protect the operator from hazards, injuries and occupational diseases. The proposed architecture is aligned with safety guidelines regarding HRC.

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