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Design considerations for safe human-robot collaborative workplaces

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Abstract

This paper deals with the design of assembly stations, where human-robot collaborative tasks are carried out. Based on the assembly process specifications, different control, safety and operator support strategies have to be implemented in order for the human safety and the overall system's productivity to be ensured. The variability of assembly processes (screwing, insertion, fixing etc.), components (small/big/flexible parts), robotic equipment (single arm, dual arm, overhead) and station layouts, dictates different approaches, in terms of human-robot interaction. Enabling technologies involve safety sensors for real time workspace supervision, certified robot control safe functionalities as well as systems for the operator's better integration into the collaborative environment via Augmented Reality and web services. The application of such concepts is examined in three pilot cases.

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Keywords: Hybrid Assembly System; Robot; Human aspect, Safety; Assembly;

1. Introduction

Over the last years, a great amount of research effort has been focused on the enablement of human-robot collaborative work cells. This is the result of an attempt to achieve high product customization by implementing flexible and highly reconfigurable production systems, which can swiftly switch between different products of varying lot sizes [1]. In this direction, the co-existence of humans and robots seems a promising solution that allows sharing both workplaces and tasks. The synergy effect of the robot's precision, repeatability and strength with the human's intelligence and flexibility is great, especially in the case of small scale production, where re-configurability efforts and costs need to become sustainable for small and medium sized companies [2].

The concept of human-robot collaboration itself is not new. Several research attempts have concentrated on the implementation of control algorithms and multi modal interfaces for the regulation of the part's movement by both the operator and the robot [3]. For example, the operator is capable of moving the robot's tool center point (TCP) bare-handedly, by exploiting force sensors and standardized voice commands or gestures in order to perform any additional functionality. At the same time, the robot can carry the part's payload and through virtual windows, ensure the collision free path. As a result, new projects [2, 4, 5] and products [6, 7] have been introduced for the exploitation of the flexibility and productivity potential of these hybrid systems, whilst a lot of research attempts have been made to investigate their benefits in depth [8].

However, there are several drawbacks that prevent them from being widely introduced to production environments. Even if the technical challenges of designing and deploying such systems have been overcome, the operators' safety will always be the primary factor for achieving acceptance. The existing applications separate the human from the robots' working areas in order for the operators' safety to be ensured. They are not designed to efficiently accommodate both types of production entities.

The aim of this paper is to investigate into different human-

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robot collaboration schemes and to discuss the safety related aspects that need to be considered during the design of human-robot collaborative applications.

2. Human-robot interaction (HRI) and collaboration

Advancements in interaction between a Human and a Robot, derives from the need for even more efficiency, flexibility and productivity, in an industrial production line, as well as for reduction in the human stress and workload. This can be achieved by simplifying the execution of the robot's tasks in the manufacturing industry, under human guidance [9, 10]. The first studies on HRI focused on remote operation, such as the Robonaut [11]. The introduction of Intelligent Assistant Devices (IADs), or Cobots, was also part of several research papers, such as [12, 13, 14]. The latest introduced IADs for workspace-sharing and time-sharing hybrid systems, since the Cobot was able to share the workspace with a co-worker, having physical contact as well. The safety in human-robot collaboration and interaction is partly a motion planning problem, according to [15]. In this paper, the human and the robot were modelled with the use of a finite state machine and the safety was achieved with the introduction of three distinct levels. These levels included the safe area, the warning area (collision avoidance and re-planning of robot motion are necessary) and the unsafe area (robot motors are driven off).

The HRI systems are categorized as either "workspace sharing" or "workspace and time sharing", depending on their function [16, 17]. However, in both categories, the human operators and robots are able to perform either single or cooperative tasks. The layout of an HRI cell as described in [18, 19], gives the human operator multiple roles. The operator also has to act as a supervisor, operator, teammate, mechanic/ programmer and bystander [20]. The HRI systems can be further categorized, depending on the level of interaction. The robot and the human operator could have a common task and workspace, a shared task and workspace, or a common task and a separate workspace (Fig. 1). In the second case, when the human operator and the robot share tasks and workspace, the relation between them is discrete.

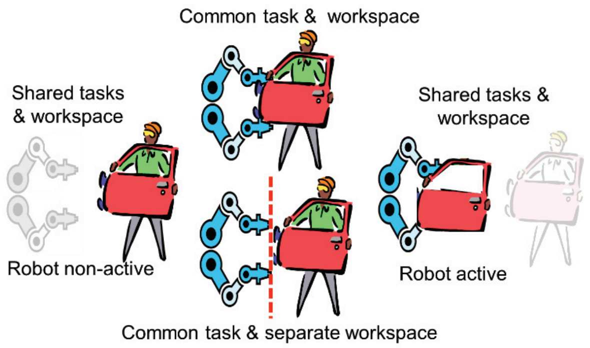

Fig. 1. Taxonomy of Human-Robot collaborative tasks and workspaces

Nowadays, a variety of manufacturing industries aspires to introduce HRI to their production lines by using as guidelines the categories mentioned above. The BMW automotive industry, introduced to their manufacturing plant in Spartanburg, cooperative robots to work near human operators in order to take over tasks that could cause human workers repetitive strain injuries [21]. Universal Robots UR10 (Matching ISO EN ISO 10218) have been applied to the BMW premises without fences, in vicinity of a human worker, in order for the door sealing to be performed. Moreover, BMW aims to introduce, in the same plant, collaborative robots that would serve as assistants to human workers by handing to them tools and parts during the assembly processes [21]. Furthermore, in the VW plant in Salzgitter, an UR – 5 has been integrated into the cylinder head assembly section of the plant for inserting spark plugs into the cylinder heads. Additionally, Audi AG, in order to optimize ergonomical issues and automate routine operations, has introduced a collaborative KUKA robot in their main plant in Ingolstadt. The robot works in close cooperation with the humans and acts as assistant in assembly operations [22].

However, in the cases mentioned above, although human operators are allowed to move around the robot, and share their common workspace, their collaboration with the robot is actually limited. Additionally, most of the robots are lightweight and of a low payload, thus not allowing for functionalities, such as strength augmentation, highly precise positioning etc. The latest research trends (e.g. ROBO-PARTNER project) envisage the interaction with industrial grade robots that enables humans to perform assembly tasks simultaneously. In this sense, the role undertaken by both should be more active and provide them with capabilities, namely the manual guidance of the robot holding the large parts, interaction with the robot by exchanging information through multi modal interfaces and so forth. The aim is to provide solutions that would enable even more direct human-robot cooperation by ensuring safe cooperation with high powered machines.

3. Safety in human-robot collaboration

In order for the human operators' safety to be ensured, over the past years different strategies have been introduced. These strategies aim at different types of safety including:

- crash safety to be ensured that only 'safe' /controlled collisions may only take place among robots, humans and obstacles. The limitation of the power/force exerted on humans is the main objective.
- active safety for timely detecting imminent collisions between humans and equipment and stopping the operation in a controlled way . Proximity sensors, vision systems and force/contact sensors, may be used to this effect.
- adaptive safety for intervening in the operation of the hardware equipment and applying corrective actions that lead to collision avoidance without stopping the operation of the device.

To this direction, national and international standards, directives and laws have been introduced to enable system integrators to easily integrate safety into their systems. Considering the fact that a collaborative workspace not only does it involve the human and the robot but also other auxiliary devices (e.g. electric screwdrivers, electrical clamping devices etc.), each cell presents unique risks that need to be handled with safety. Therefore, the standards and laws for each type of equipment and operation should also be respected. Tables 1, 2 and 3, summarize indicative examples of the most known laws and general standards in EU.

Table 1. EU Directives

Title	Description
2006/42/EC	Machinery Directive (MD)
2009/104/EC	Use of Work equipment Directive
89/654/EC	Workplace Directive
2001/95/EC	Product Safety Directive
2006/95/EC	Low Voltage Directive (LVD)
2004/108/EC	Electromagnetic compatibility Directive (EMC)

Table 2. Indicative general standards

Title	Description
EN ISO 12100	Safety of machinery - General principles for design - Risk assessment and risk reduction
EN ISO 13849-1/2	Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design, Part 2: Validation
EN 60204-1	Safety of machinery - Electrical equipment of machines - Part 1: General requirements
IEC 62061	Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems

Table 3. Robot standards

Title	Description
EN ISO 10218-1	Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots
EN ISO 10218-2	Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration
ISO/PDTS 15066	Robots and robotic Devices – Collaborative Robots

Presently, there are almost 30 active EU directives and around 600 different standards related to safety. Specifically for robotic cells, the first three standards of Table 3, foresee a plethora of different strategies to achieve safety. The most important ones involve:

- **Safety-related control system performance:** Safety-related parts of the control systems have to ensure that tolerance in single faults can be achieved without compromising safety.
- **Robot Stopping Functions:** Every robot is required to have protective stop function as well as independent emergency stop function. They should also provide connection to external safety equipment.
- **Speed Control:** The speed of the robot end-effector and of the tool centre point (TCP) need to be controllable. Especially for collaborative workplaces the speed of the TCP should not exceed 250 mm/s.
- **Collaborative operation requirements:** Robots designed for collaborative operation should provide a visual indication when the robot is in a collaborative operation. The following requirements are applicable:
  - **Safety Rated Monitored Stop.** The robot needs to stop when a human is in the collaborative workspace and may resume automatic operation when the human gets out of it.
  - **Hand guiding.** Hand guiding equipment needs to include an emergency stop and an enabling device. During this operation, the speed of the robot ought to be monitored in a safety certified way. Several technologies such as impedance or stiffness control may be used to enable hand guiding by human.
  - **Speed and position monitoring.** The robot has to maintain from the operator a separation distance, monitored by integral features or a combination of external inputs.
  - **Power and force limiting by inherent design.** The power/force limiting functions should respect the limits set by the standards and if exceeded, a stop should be issued.
  - **Power and force limiting by control system.** This foresees that a control function be used to ensure that the maximum values of power and force should not be exceeded.
- **Limiting Robot Motion:** Safeguarded space at the maximum workspace dimensions could result in the enclosure of an unnecessarily large area. Limiting the motion of the robot can be achieved by the robot's integral systems (e.g. safety-rated soft axis and space limiting or hard stops), by installing external limiting devices, or by a combination of both. Dynamic limiting through control devices (switches, light curtains etc.) can be used to further limit the robot's motion while executing its program.
- **Establishing minimum separation distance:** Depending on the application, there is a risk assessment used in order for the minimum separation distance, between the robot and the operator to be determined. The assessment considers a) The hazards associated with the end effector and the parts it may hold, b) the workspace layout c) the operators' tasks and d) the system's usability
- **Collision detection:** The safety function needs to determine whether the current positions and velocities of both the robot and the human can cause the separation distance to decrease below the minimum value (collision).
- **Avoiding potential collision:** This function allows the robot to avoid a potential collision by: a) Slowing its speed or pausing; b) Reversing course along its path; c) Executing another safe path
- **Technological and ergonomical requirements:** In case of a possible collision between a human and a robot, caution should be exercised in order to ensure that no sharp, pointed, cutting edges or rough surfaces are found in the contact area. Moreover, the ambient working space, in which a person may collide with a collaborative robot, needs to be designed in such a way so as to provide the user with sufficient space to move around, thus avoiding clamping situations

These functions have been designated by the standardization bodies to control different safety aspects without overlapping. However, overlapping may occur in the customization process of each application and has to be reviewed about the completeness of coverage of the functional safety requirements.

4. Human considerations

The design of human-robot coexistence and collaborative cells, as well as the effective task allocation between a human and a robot are also closely connected to social-physiological issues. The better understanding and prediction of the human behaviour, as well as the improvement of HRI, are partly related to cognitive engineering, psychology and sociology. Trust, workload and risk have been identified as the major human factors affecting the use of automation technologies. The human centered robotic cell design, according to [23], is mainly affected by human factors, such as workload, vigilance, situation awareness, errors etc. as well as by cognitive engineering related aspects and ergonomics. In [24] the influence of industrial robot motions in human-robot cooperative cells has been presented. The results have shown that unpredictable robot motions have reduced the humans' well-being and performance and were not suited for HRI applications

5. Case studies

Three case studies are presented on the basis of different safety requirements.

5.1. Case 1: Automotive dashboard preassembly

The first case is based on a passenger vehicles dashboard preassembly scenario in the automotive industry. In its current state, the loading of the traverse and the assembly are performed by a human worker. The traverse is the longitudinal component found behind the vehicle's dashboard. After the loading of the traverse to the station has taken place, several parts are installed, including a body computer, and a cable connected to it and fixed on the traverse, with the use of clips in multiple points.

In the development of a hybrid solution, the loading task and the assembly of the body computer have been assigned to a Dual-Arm Robot by COMAU. The scenario starts with the transport of the traverse from a loading area to an assembly bank, where the assembly will take place. After it has been placed on the assembly base, the robot, using both hands, grasps the body computer, and places it on the traverse. The body computer needs to be screwed on the traverse therefore, the robot uses a modified gripper capable of picking a conventional screwdriver in order to screw the Body Computer. During this operation one arm holds the computer in place and the other one performs the screwing. The setup is shown in Fig. 3.

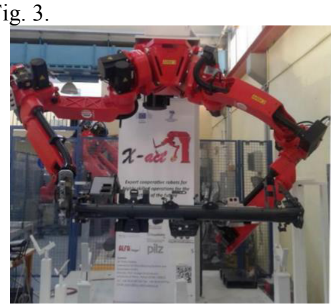

Fig. 3. Dual arm assembly area

Finally, after the screwdriver is returned to its base, the installation of the cable is carried out in cooperation with the human. During this stage, the robot has grasped and picked up the cable from its original position, holding it in front of the assembly bank in order to be reached by the human. The worker approaches the robot, gets the cable and installs it on the traverse and the Body Computer using the plastic pins.

However, because these operations require a fenceless approach, the issue of safety is essential not only during the cooperative task, but also throughout the entire program's execution by the robot. To this effect, a PILZ Safety Eye has been used. The Safety Eye is basically a camera, placed on the roof above the cell, overlooking it and the surrounding area. The user of the Safety Eye, with specially designed markers, is free to divide the cell into smaller zones (volumes) according to its functionality. The Red Zones (Detection Zones) act as Emergency Safety Switches, cancelling all of the robots' motion when someone steps into them. The Yellow Zones (Warning Zones) inform the workers about their proximity to the cell, in order to prevent any unwanted, accidental stops of the program execution by the robot, which would stop the production line.

In this scenario, during the robot tasks execution, one warning and one detection zone have been used, in order to enable the robot to stop its motion when the human is in proximity (Fig. 4(a)).

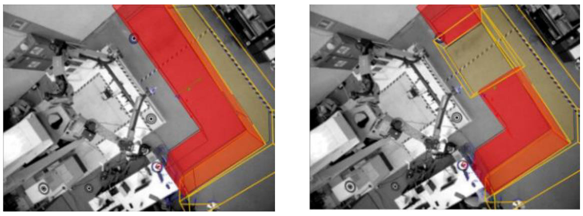

Fig. 4. (a) Robot tasks-zone arrangement 1; (b) HR collaboration- zone arrangement 2

For the proper execution of collaborative tasks, a different zone arrangement has been used (Fig. 4(b)). In these zones, the operator may enter the warning zone in front of the robot to execute a task. The robot's speed is limited to 250mm/s.

5.2. Case 2: Automotive rear suspension assembly

In this case, a high payload robot is used in order to support the human by performing the loading of the axles and the rear wheel groups. The axle loading is solely carried out by the robot, while the wheel group assembly requires the cooperation between the robot handling the weight and the human, who uses his hands to directly adjust the position of the parts to be assembled (Fig. 5). More specifically, the robot automatically picks up the wheel groups and brings them to the left/right of the axle, opposite to the holes that are used for screwing. Following, manual guidance is applied by the human for the correct alignment of the part against the holes. In this collaboration scheme, the heaviest part lifted by the operator is that of the screwdriver (1.5kg). After the assembly of the first wheel group and while the human performs delicate tasks (cable assembly, clip insertion etc.), the robot continues bringing the second wheel group, by avoiding any collision with the human. At any time, the operator can guide the robot through gestures or audio commands.

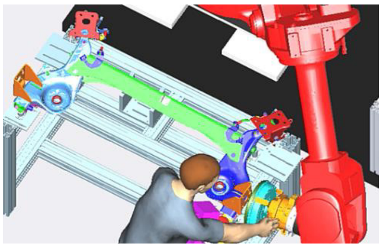

Fig. 5. Human-robot collaborative assembly – Manual guidance

The difference with the previous scenario is that the human actively guides the robot with his hand in order to fine tune the positioning of the parts. During the manual guidance the robot's position is confined inside virtual volumes being monitored by the robot controller. When the robot moves in the auto mode, the SafetyEye system is used so as to reduce the robot's speed or stop its motion in case the human is in proximity. When the human is outside the monitored area, the robot moves at full speed and the speed is reduced to the safe value if the human enters the warning zone.

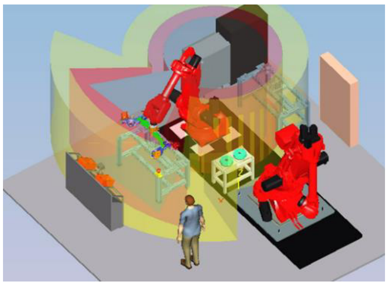

Fig. 6. Space monitoring using virtual zones (Safety Eye sensor)

5.3. Case 3: Refrigerators assembly

The last case study brings the human even closer to the robot by considering the concurrent assembly and the sealing of a refrigerator in a serial assembly line. The introduction of robots in this case allows for the reduction in tape application, which accounts for a great amount of reworked products. A new sealing technique using a hot sealant can be introduced. The robot is positioned next to the human and can operate either in automatic or in the hand guiding mode. When the refrigerator enters the station, the human prepares the components and the robot starts applying the sealant.

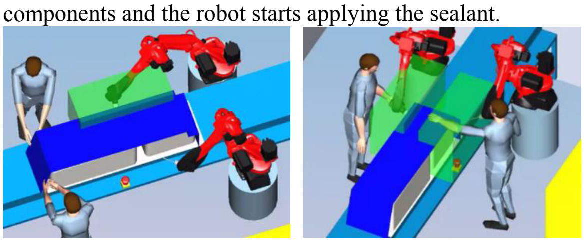

Fig. 7. (a)Human-Robot concurrent assembly – Safe zones; (b) Human guided application of sealant by robot.

The operator continues to assemble pipes and cables at the back of the product as shown in Fig. 7 (a). Since the assembly is quite loose, the sealant may not be properly spread on the desired surface. For this reason, the human can grasp the robot and lead it to a different path by applying more sealant where necessary. This is an indicative example of how the human cognition is combined with the robot's capabilities for the provision of a high quality process.
However, and unlike the previous two case studies, the requirements for co-existence are such that do not allow for space separation. The human and the robot have to work in a very small area, consequently, the use of overhead cameras for supervision cannot be considered a feasible solution. In this context, power and force limiting techniques need to be applied in parallel with reduced speed and safe monitoring of the robot's speed and position. The limitation of the working envelope and the tool orientation is also necessary to ensure that the hot end effector not come in contact with the operator's body. Current industrial robots offer their own solutions for safely limiting the workspace (e.g. Interference Regions by COMAU). The safety strategy also calls for different equipment, such as tactile/capacitive skins that allow the real time detection of contact with the human or pressure sensitive floor mats capable of tracking the position of the human. Some laboratory applications have managed to track the human via sensors, namely the Kinect in order for his posture to be estimated; however, they cannot be certified or be ensured that their field of view is free of obstacles. The aforementioned solutions apply to the stage where the robot needs to move independently of the human. In the case of manual guidance, the robot needs either to be directly commanded by the human or to recognize the contact of the human hand and switch to a more compliant control strategy that will allow the human to guide the robot with his hands (e.g. compliance or impedance control). Table 1 summarizes the collaboration methods and safety functions for each case.

Table 1. Summary of safety functions for each case.

Collaborative methods	Case 1	Case 2	Case 3
Speed & Separation Monitoring	X	X	
Power & Force Limiting			X
Hand Guiding		X	X
Safety functions	Case 1	Case 2	Case3
Safety monitored stop	X	X	X
Enabling Device		X	X
Safety-Rated Monitored Speed	X	X	X
Safety-Rated Reduced Speed	X	X	X
Safety-Rated soft axis	X	X	X
Space to Stop Monitoring	X	X	X
Deceleration Monitoring	X	X	X
IR: Cartesian Regions		X	X
IR: Cartesian Safe Limited Position		X	X
Safe Tool Orientation		X	X
Force and Impedance Control		X	X
Collision Detection			X
Collision Avoidance			X

Based on the required collaboration method, the different safety functions are selected and combined to create a safety concept. The description and analysis of the mechanisms that are used to implement these functions extends beyond the scope of this paper and has to be done on an individual basis. The completeness of the functions in Table 1 is ensured by the TS 15066 application guidelines complemented by a detailed risk assessment which is mandatory for each implementation.

6. Discussion

This paper has investigated multiple aspects of safety that should be considered during the design and deployment of human-robot collaborative work cells. A detailed analysis of the existing standards, available technologies and human acceptance has enabled the identification of the main challenges that need to be addressed by the integrators of hybrid assembly systems. The three different use cases have exposed different requirements that originate from:

- the type of the robot (dual/single arm),
- the robot's payload and power/force that it can apply
- the part's characteristics (geometry/weight)
- the assembly/manufacturing process used, considering the end effector and robot's motion.

As a conclusion, it can be stated that the above variables affect the type of equipment and the layout to be used in each case. Fenceless separation monitoring requires a lot of clearance between the human and the robot in order for the supervision system to be effective. On the other hand, close cooperation has reduced requirements (provided that the human is not constrained) but requires far more advanced sensing capabilities for collision detection and avoidance. Based on the user's acceptance, human operators feel more comfortable when they are aware of the underlying safety functionalities by using their senses. In this context, the workplaces need to be designed so that different interfaces such as visual, audio and tactile can be used.

Future work should focus on developing methods for better immersing the human in the new safe measures that are becoming available. A good example is the introduction of augmented reality techniques that allow for the visualization of the robot operating/safe areas. Moreover, future research should focus on integrating the safety induced restrictions inside design and planning tools that can efficiently simulate their effect on the manufacturing process.

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