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Design of Human Robot Collaboration workstations – Two automotive case studies

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Abstract

Human Robot Collaboration assembly cells benefit the capabilities and skills of both industrial robots and humans, although fenceless coexistence leads to issues related to safety and human-system interaction. A series of methods for hybrid workstation design focusing on safe yet efficient Human Robot Collaboration is presented, where various layout configurations are illustrated and evaluated aiming industrial implementation. Two distinct automotive use cases, with different requirements and challenges, are used as reference for highlighting particularities on lightweight and high-payload robots, in addition to small and large size product assemblies.

Keywords: hybrid assembly cell; human robot collaboration; workstation design; safety; lightweight robot; high-payload robot

1. Introduction

In recent years, industry focuses on increasing flexibility and productivity of their production lines besides decreasing product defects, cycle times and other costs related to reworking and error handling [1]. In cases where existing lines are optimized to draw level to modern industry requirements, balancing of flexibility and productivity is one of main objectives [2]. Hybrid cells and assembly lines combine the benefits of both human operators and industrial robots offering high flexibility and productivity potential besides reduction of cost and ergonomics improvement [3]. Based on this approach, a series of hybrid cells have been deployed or prototyped in different industrial sectors including automotive[4,5], home appliances [6], composites [7], aerospace [7], etc.

According to the ISO 10218-1:2011 [8], "collaborative workspace" is a "workspace within the safeguarded space where the robot and a human can perform tasks simultaneously during production operation". The degree of interaction between human operators and robots has been categorized in several reports [9–11] . All approaches classify the levels of human robot interaction (HRI) according to the existence of shared workspace, contact or co-manipulation of objects. In 2016, TS/ISO 15066 [12] standardized the operation modes and subsequently interaction levels into: a) safety-rated monitored stop b) hand guiding c) speed and separation monitoring d) power and force limiting. The interaction levels for every hybrid cell are predefined by the requirements of the manufacturing process and the deployed solutions. Each interaction level requires different perception systems for ensuring safety. According to ISO 10218-2:2011 [13], safety related parts of control system should comply with "Performance Level d, Category 3". Devices of this category ensure that any kind of fault is detectable and does not lead to any loss of safety function. However, they increase implementation costs and in some cases are not sufficient for certifying complex envisioned solutions. Subsequently, systems established on fenceless HRI are not widely spread into

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industrial shop floors considering that operators' safety will always be the main baseline for achieving acceptance.

Another aspect that limits wide Human Robot Collaboration (HRC) industrial implementation is human factors. Fenceless coexistence can lead to discomfort of operators especially in greater levels of interaction. Several studies focused on defining human factors that need to be considered during design phase. "Situation awareness" [14], "stress quantification" [15], "concentration or sustained attention" [16] and "task switching" [17] have been classified as important factors [18]. Towards expediting human acceptance and trust to the system, academia and businesses emphasize on the development of advanced Human Machine Interfaces (HMIs). Those HMIs provide real-time information to operators about system and robot state and in parallel monitor operator's status for enabling system cognition. Different solutions have been deployed including Augmented Reality applications and smartwatches [19] for illustrating robot trajectories, safety zones, tasks instructions, etc. but also giving the capability to the operator of providing feedback to the system. Focus has also be given on the development of pioneer supervision frameworks in terms of task dispatching, execution, monitoring and control [20,21]. In contrast with traditional execution systems, those frameworks are able to handle stochastic events, caused mainly by operators, and orchestrate process execution. Another approach that is mainly investigated in academia is dynamic robot motion planning. Different methods [22–24] have been deployed focusing on how robots can maintain their speed and proactively update their trajectory for avoiding collisions. The main drawback of all those coordination or path planning systems is that their processing modules besides perception devices are not certificated. Thus, the interaction potential they offer is excluded from industrial applications.

Current industrial practice mostly uses "safety-rated monitored stop" due to the simplicity of safety systems. The main drawback of this approach is that robots safeguard or reduce speed by any minor infringement of safety zones. An overprotective safety zone configuration can lead to unnecessary robot stopping since human intentions are not known [25]. This causes a negative effect on cell's Key Performance Indicators, product quality and hardware stress. Stochastic fluctuations on robots' speed or status make hybrid solutions immature for industry.

An innovative cell or line design can address many of the aforementioned handicaps. The most crucial aspect that needs to be considered is safety, in terms of current safety standards and available safety devices. In addition, the positioning of human, robot or hybrid workstations is also important, since safety zone dimensioning and robot speeds must comply with ISO-15066. Finally, assembly line balancing besides resource or part circulation for the assembly process has a decisive effect on seamless process execution. Different methods for resource or part circulation have been enlisted and proposed [1]. The selection of method is mainly depended on use case requirements. In terms of workstation design, there is scientific focus on design considerations. Previous work [26–29] aims on defining different HRC schemes and safety concepts during design phase. This work aims on proposing methodologies for designing hybrid workstations conforming current safety standards besides minimizing fluctuations on Key Performance Indicators (KPIs) due to stochastic events. Two different case studies originating from automotive industry will be discussed in two different sections of this manuscript in respect to the particularities of lightweight and high-payload robots besides small and large size assemblies.

2. HRC workstation – Lightweight robot

2.1. Use case description

This use case comes from the powertrain sector and deals with the assembly of a EURO6 turbocharger (TC). The assembled product is consisted by a series of components with different characteristics in terms of geometry and mass. The main part is the TC housing that weighs over 8.5kg. All other components are lighter and are fastened on the TC housing. The assembly procedure requires high dexterity skills considering the complexity and variety of components' geometries. Heavy object manipulation and high repeatability tasks emerge ergonomic issues, thus they need to be automated.

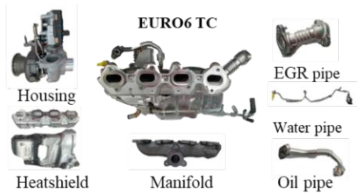

Fig. 1. Turbocharger assembly and components.

Full automation of the assembly process might be possible, although the flexibility of the solution would be minor, and the implementation costs could make the cell unsustainable in economic aspects. Subsequently, semi-automation of the process, with the use of HRC, is the most suitable solution by allocating non-ergonomic or high repeatability tasks to robots. In contrast, human operators will be responsible for tasks requiring dexterity. For this use case, lightweight collaborative UR10 robots, already approved for high interaction levels, can be used. Those robots monitor forces at their end-effectors and body and are able to slow down or stop for protecting operators during collisions or hand guiding. Thus, required peripheral safety systems or end-effector enhancements are limited, and system certification is possible through innovative workstation design. The proposed solution should comply with a series of KPIs and requirements. At first, operator safety must be certified by standards and regulations. Moreover, cycle time has to be less than 60 seconds and implementation costs should ensure sustainability of the solution. Last but not least, ergonomics must be improved over 30% in comparison with current practice. On the following subsections, two workstation design concepts are presented and discussed for this case study.

2.2. Workstation design – Concept 1

In this scenario, focus was given on maximizing human safety and ensuring that cycle time constraint is achieved. The baseline of this solution is the deployment of distinct human and robot workstations separated by safety zones (Fig. 2).

Safety zone monitoring can be achieved with optoelectronic devices like laser scanners or light curtains at zone boundaries. Resource positioning is fixed, and a conveyor system is used to circulate the assembled workpieces between the workstations. "Safety-rated monitored stop" approach is used, meaning that cobots can perform high-speed movements and would slow down or safeguard only in case of safety zone infringements. Distinguishing the workstations makes human presence inside the robot workstation unnecessary, except in cases of error handling, thus fluctuations on cycle time are rare. Moreover, human comfort and system acceptance is maximized since interaction levels remain low similarly to current practice.

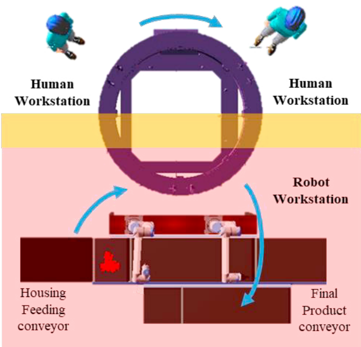

Fig. 2. Concept 1 layout top view and safety zones.

After allocating and balancing tasks between cobots and human operators, the following workstations occur:

- Cobot workstation: There are two collaborative robots that execute the non-ergonomic tasks. In detail, the first robot manipulates the TC housing and final assembly by performing Pick and Place (PnP) actions between conveyor systems. In addition, this robot supports the second one by executing some of the fastening operations. For fastening, both robots manipulate push-to-start screwdrivers and apply torque on pre-positioned fasteners.
- Human operator workstation 1: An operator assembles the first two components (manifold and EGR pipe) on the TC housing by manipulating the parts and positioning the corresponding fasteners.
- Human operator workstation 2: A second operator assembles the remaining components (oil pipe, water pipe and heatshield) by manipulating the parts and positioning the corresponding fasteners.

In terms of control, conventional certified systems can support the particularities of the concept. A PLC system may trigger next assembly phases, for workpieces circulation, as soon as all operators and robots communicate that they completed their tasks (i.e. DIO signals). The main drawback of this solution however is the inexistence of collaborative working areas, thus flexibility potential is reduced. Lastly, the internal conveyor system increases implementation costs.

2.3. Workstation design – Concept 2

This concept focuses on achieving high flexibility, by implementing hybrid workstations but also ensuring that human intrusions inside robots' working areas are limited. The baseline of this approach was having multiple assemblies performed in parallel (Fig. 3). On each assembly, an alternation of robot and manual tasks will take place. More specifically, on each workstation an assembly, consisted by four time-balanced stages, may take place, as follows:

- Stage 1: A human operator assembles the manifold and the EGR pipe on the TC housing, that is pre-loaded by a cobot on the fixture. After part assembly and positioning of corresponding fasteners, the operator leaves the workstation and moves to the one next to him/her.
- Stage 2: A cobot manipulates a screwdriver and secures the assembled components of "stage 1".
- Stage 3: At this stage, if the corresponding operator has performed his/her tasks at nearby workstation and "stage 2" is completed, she/he returns for assembling the remaining TC components.
- Stage 4: After completion of "stage 3", a cobot manipulates a screwdriver for securing the final components. Moreover, it PnP the product from the fixture to the conveyor. Finally, the cobot PnP a new TC housing on the fixture for initiating next assembly cycle.

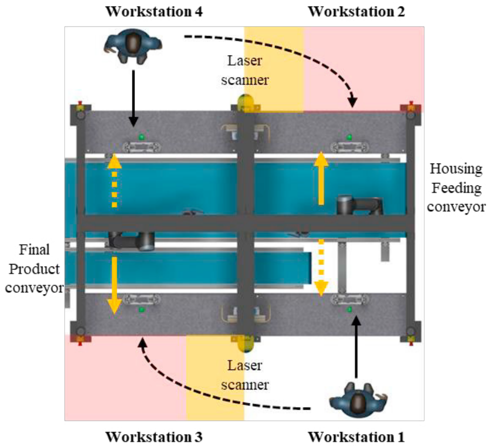

Fig. 3. Concept 2 layout top view and safety zones.

In terms of safety, this hybrid cell design can support all modes of operation, as enlisted in ISO-15066, by implementing two laser scanners, without any fluctuations on robot performance. This is because appropriate dimensioning and spacing between the workstations permits high-speed robot movements that are difficult to be affected by human presence. In detail, the relative speeds between cobots and operators, who work on nearby workstations, are either negative or tend to zero, thus they are in line with certified limits. Dynamic safety zone reconfiguration is implemented meaning that "normal", "reduced" and "safeguard" zone dimensioning and positioning is updated according to the layout status. More specifically, a human centered approach is used meaning that on each side of the cell the "normal" areas are located on the workstations where manual tasks should be executed. In case human operator improvises and moves to the wrong station the cobot will slow down and a notification will be appeared. All safety devices are connected to a safety PLC. Regarding control, a PLC module is connected to robot controllers and workstation buttons (for operators), ensuring synchronization of assembly stages. In overall, the existence of hybrid workstations ensures flexibility in case of production changes or error-handling besides reduces implementation cost due to inexistence of internal conveyor systems.

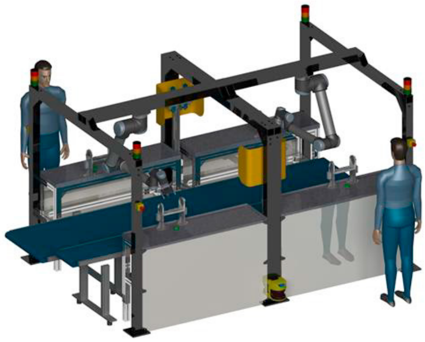

Fig. 5. Concept 2 layout isometric view.

2.4. Implementation

The two concepts where evaluated by simulation models for assessing their performance in terms of task balancing, cycle time, robot reachability, zone dimensioning, etc. Both solutions complied with the cycle time constraint, however "Concept 2" was most favorable by the end-users. Referring to Table 1, dispatching all manual tasks to workers, instead of having groups of tasks to different operators, reduced the repeatability of manual operations and thus improved metrics. Moreover, this concept presents greater flexibility due to supported types of HRI and comes in an acceptable and sustainable integration cost. A demonstrator (Fig. 4), based on the industrial version of "Concept 2", has been implemented for validating the performance of resources and evaluating human factors. Testing proved that dynamic zone reconfiguration for seamless HRC is feasible. Thus stability, in terms of cycle time and product quality, is achieved. Surveys on different persons proved that human acceptance is high and HRC is desired and thrusted. Finally, the cell was certified by Denmark's Notified Body after performing risk assessment in respect to current safety standards and regulations.

Table 1. Technical specifications of proposed solutions.

	Cycle time (sec)	Cost (€)	Ergonomics Improvement (RULA)	Supported modes of operation (ISO-15066)
Concept 1	43	71000	40%	a
Concept 2	48	56000	55%	a, b, c, d

3. HRC workstation – High-Payload robot

3.1. Use case description

This use case originates from the chassis sector and deals with the assembly of doors on pick-up cabs. The assembly operation involves the manipulation of heavy objects (i.e. front and back doors), using hoists, as well as a series of high dexterity actions including harness connection and fastening. In parallel, for assembly line balancing purposes, the assembly of components on the vehicle's bed might also be executed. In current practice, the assembly operation is manually performed by operators. Feeding mechanisms deliver doors to the workstation and human intervention is required for loading doors on the hoists. Once a door is loaded, the operator guides the hoist to the assembly area and assembles the door by fastening the door hinges and connecting harness. For each cycle, the same procedure is executed for both front and rear doors. A key feature of the operation is that the chassis is positioned on a constantly moving conveyor, with a speed of 3,35m/min.

Fig. 4. Hybrid cell demonstrator at LMS premises.

Fig. 6. Door assembly components.

Manipulating the hoist for door positioning, applying fasteners, connecting harness and in parallel following the car emerges ergonomic issues. In addition, cycle time reduction is pursued for the following years through optimization of the production line. Hybrid automation seems to be the optimum solution since many of the involved tasks require dexterity and improvisation. Because of the mass of the assembled doors, in addition to the movement of the chassis, a non-collaborative high-payload robot positioned on a linear gantry is needed for the case. The following section discusses a scenario for ensuring seamless HRC on this industrial case study.

3.2. Workstation design

The proposed layout (Fig. 7) is based on the existing solution in terms of resources and dimensioning. The conveyor line that transfers the chassis remains the same. On the other hand, the hoist system is replaced by a high-payload robot attached on an overhead gantry rail for increasing its working area envelope. An encoder is implemented on the conveyor and is connected to robot controller enabling chassis following. Moreover, the door feeding mechanisms are enhanced with pneumatic actuators for enabling automatic door picking by the robots, without human intervention. The optimized assembly procedure is envisioned in four stages, as follows:

- Stage 1: Robot arm PnP front door from feeding mechanism and approaches chassis. In parallel, human operator performs tasks at pick-up's bed for assembly line balancing.
- Stage 2: Operator collaborates with robot for assembling front door. Robot positioning fine-tuning is performed by operator via manual guidance. Robot supports the door while operator connects harness or fastens door's hinges.
- Stages 3&4: Same as stages 1 and 2, although they relate to back door assembly.

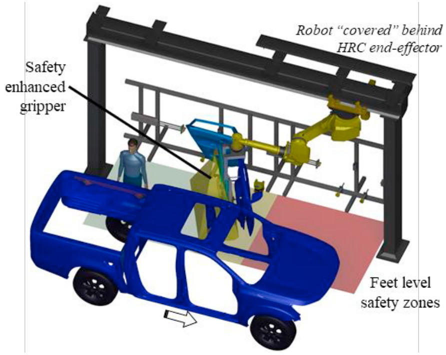

Fig. 7. Hybrid cell overview.

Stages 1 and 3 interaction level is low, thus "safety-rated monitored stop" besides "speed and separation monitoring" will be used. During collaborative door assembly of stages 2 and 4, "hand guiding" and "power and force limiting" are used. Considering that high interaction levels occur, and the selected robot is not certified as collaborative, the design methodology focuses on having the operator interacting with a resource (i.e. robot end-effector) that actively or passively safeguards him/her. More specifically, robot's approaching configuration will always ensure that the safety enhanced end-effector is inserted between robot and operator. Robot arm's body will be inside "red" zone and safety enhanced end-effector inside "yellow" zone. The zones will be constantly monitored and updated by a laser scanner on floor level. Moreover, the robot's arm body is unreachable by operator due to the overhead configuration.

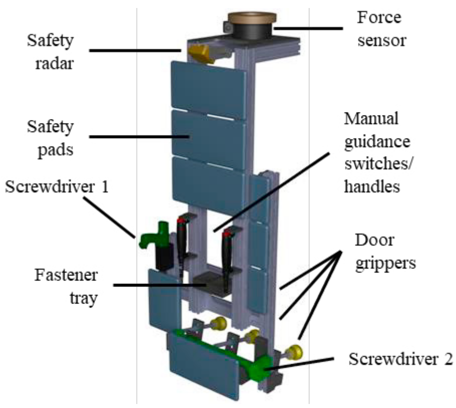

Fig. 8. Safety enhanced end-effector.

Aiming safe HRI, a specialized robot end-effector is developed having a series of safety features (Fig. 8). At first, the contact surfaces were increased, made smoother and methods of absorbing energy were introduced. Safety skin pads [30] in combination with a force sensor enable "power and force limiting" safety control. Certified grip enabling switches are used for "hand guiding" HRI during fine-tuning of door positioning. Finally, a safety radar zone monitoring device is integrated near gripper's mounting flange. The purpose of this device is ensuring that upper human body collisions are avoided, by deploying a safety zone covering the end-effector during non-collaborative robot trajectories.

3.3. Implementation

In current project phase, the proposed solution has been verified in terms of operation feasibility, cycle time, etc. in a simulation environment. The models assessed also dynamic zone reconfiguration and validated that cell's design empowers seamless HRC and interaction without fluctuations on KPIs due to unexpected starts and stops.

4. Workstation Design Methodologies

Referring to the concepts discussed for both case studies, two design methodologies or considerations can be extracted. The first is the implementation of assembly process balancing where human and robot tasks are separated into distinct stages where interaction levels remain low. Parallel execution of those stages on different areas of the cell enables high production rates since both human and robot resources can work with higher efficiency and no intrusions. The positioning and selection of non-collaborative (e.g. Section 2.2) or collaborative (e.g. Section 2.3) areas for a cell effects the flexibility of the solution as well as the safety systems required for certification. The second design methodology mostly addresses the challenge of safety with high-payload robot. It suggests that since the robot is not directly suitable for fenceless HRI, the operator could interact with an end-effector that can support all types of interaction. For achieving this, safety devices for "separation monitoring", "power and force limiting" and "hand guiding" are necessary (e.g. force sensors, safety skins, enabling devices, e-stop buttons, optoelectronic devices, etc.). The selection of the sensors is mostly depended on the particularities of the use case. Based on this approach, the end-effector should be the only component of the robot that is accessible by the worker during collaboration. Robot arm's body or any other resource that cause injuries during operation must be located inside safeguard stop zones. During robot movement, dynamic safety zone reconfiguration will ensure that: a) the robot is enclosed by safety zones b) robot trajectory speed will remain below 250mm/sec during HRC, as regulations suggest. For cellular assembly manufacturing, a combination of both methodologies can be applied in cases were high-payload robots are required for large size assemblies.

5. Conclusions and future steps

The proposed hybrid workstation design concepts focused on achieving assembly process execution without fluctuations on KPIs due to unexpected safety zone infringements. Aiming certification, seamless HRC is intended to be accomplished through layout design methods, based on certified safety sensors, instead of path planning algorithms for collision avoidance. The methods involved layout arrangement or resource circulation frameworks, in addition to the implementation of safety strategies for different levels of interaction. Based on requirements of industrial cases and safety standards, the concepts have been verified on physical demonstrations or simulation environments. Testing validated that proposed workstation design facilitated human acceptance and empowered human comfort and trust to the system. Two design methodologies have been extracted through validated concepts of two case studies. Future work includes the implementation of a physical demonstrator for the verification of the high-payload robot concept. In addition, it includes the validation of concepts' advantages on other industrial applications. The presented high-payload concept is strongly supported by the movement of the robot on the gantry and reconfiguration of safety zones. Regarding the concepts of Section 2, the implementation of non-collaborative robots for larger product assemblies could compromise key features of the discussed concepts. Subsequently, documented methodologies of the manuscript will be further investigated aiming their normalization on multiple types of robots and assembly sizes.

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