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Safety, Ergonomics and Efficiency in Human-Robot Collaborative Assembly: Design Guidelines and Requirements

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Abstract

The introduction of Industry 4.0 technologies and automation in production and assembly is progressing and bringing a number of changes. While automation in the past was planned and implemented mostly independently of the operator, due to a clear separation of automated processes and manual activities, this has changed considerably in today's production environment. The operator increasingly works directly with the machine or robot which supports the human in manufacturing or assembly activities. However, with the introduction of collaborative robots in assembly, many companies are faced with the challenge of making their workplaces safe and ergonomic. While collaborative robots present some inherent safety measures which allow the implementation of safe applications, this state usually changes as soon as they are integrated into a working environment and equipped with different type of end-effectors. In addition, ergonomics and efficiency are often ignored. Therefore, new design guidelines for systems integrator designer are needed to develop safe and ergonomic collaborative assembly workstations without neglecting production efficiency requirements. In this paper, a collection and classification of prerequisites and design guidelines are developed starting from international standards, research works and real use cases. These guidelines will support application designers to proper develop and evaluate safe, human-centered and efficient collaborative assembly workstations. Not only the safety of the robotized components is considered, but also a holistic approach is chosen in which operators, the manufacturing and assembly system as well as organizational aspects are examined and summarized within the framework of collaborative assembly.

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Keywords: safety and ergonomics; collaborative robotics; industry 4.0; human-robot collaboration

1. Introduction to industrial human-robot interaction in human-centric assembly workstation

Due to the fact that modern production systems are gradually shifting from mass production to mass customization [1], manufacturing companies have to adjust their process by improving production efficiency, flexibility and sustainability. The actual industrial transformation which is deeply changing worldwide companies is conceived through the concept of the fourth industrial revolution or "Industry 4.0" [2]. Industrial collaborative robotics is one of the key cyber-physical enabling technology of Industry 4.0. The aim of human-robot interaction (HRI) is to combine automation strengths with unique human skills by allowing a safe and profitable task sharing in a fenceless and common workspace. The implementation of human-robot shared workstations aims to improve operators work conditions while increasing production performance at the same time. This could be particularly interesting especially in case of collaborative assembly, which is one of the most attractive and discussed application of HRI in industry. Actually, a proper use of collaborative robots for the support of operators during assembly tasks will be a good example of the so called "human-centered design". Basically, it aims to consider the operator work conditions the main element of the production system by improving human wellbeing, user satisfaction, sustainability and accessibility and preventing the

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negative effects related to operator's health, safety and performance at the same time [3]. The possibility to use collaborative robots in hybrid workstations opens new opportunities but also new challenges, especially in terms of operator's occupational health and safety and work organization. From the assembly workstation design prospective, main critical points could be:

- How to manage occupational risks for health and safety of operators?

- How to implement an ergonomic solution booth from the physical and cognitive point of view?

- How to plan and optimize the use of production resources (human and robot) for the assembly tasks?

This work aims to answer these questions by developing a set of design guidelines for a proper implementation of a safe, ergonomic and efficient HRI in shared and human-centric assembly workstations.

2. Preliminary concepts for the design of human-robot assembly workstations

The design of a human-robot assembly workstation implies a parallel integration between product and process. This is necessary since industrial HRI requires particular attention to occupational health and safety conditions, which can be satisfied more effectively trough a proper and integrated consideration of the related requirements during the early product and process design stages. In this context, a common and useful design methodology is Concurrent Engineering (CE). It is a systematic methodology for the simultaneous and parallel implementation of products and process design activities and involves different design disciplines among the entire product lifecycle [4]. According to this principle, a complete design of a human-centric HRI should include the definition and the analysis of product features, assembly cycle, robot systems, workstations features/layout, operator psychophysical features (and requirements) and the effects of their relationships on each other. Ideally, this should also include and balance the requirements in terms of safety, ergonomics and production efficiency (see Fig.1).

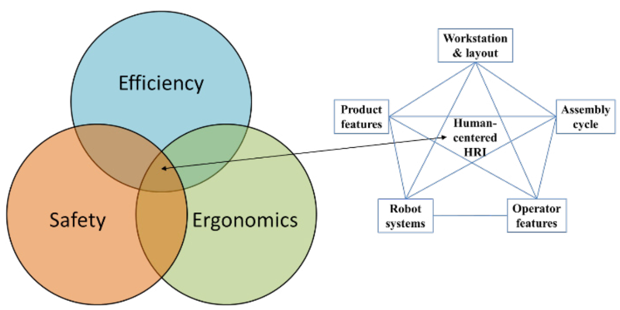

Fig. 1. Considerations for the design of human-centric industrial HRI.

When the design of a new human-robot assembly workstation is required, it is supposed to have three main possibilities (see Fig.2):

- Design a new workstation by starting from an existing one, which means that the product features and the related assembly cycle have already been defined;
- Design a new workstation by starting from zero but with defined product features and related assembly cycle;
- Design a new workstation by starting from zero without defined product features and related assembly cycle;

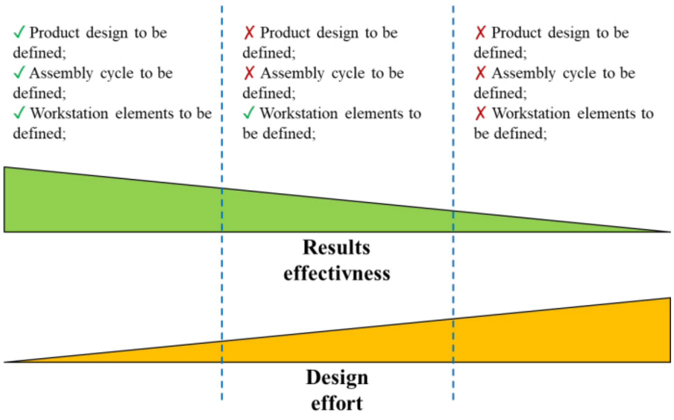

Fig. 2. Design effort according to different starting situations for the implementation of a new human-robot assembly workstation

The different constraints in terms of initial conditions will deeply affect the design complexity of the workstation layout and, as a consequence, the effectiveness of the final results.

According to these concepts and considering the assembly functional requirements, the technics, the technology, the economics and the sustainability constraints, the main and general requirements to be satisfied through the design of the workstation layout are:

1. Minimize the occupational risks (especially the mechanical one) for health and safety which can occur during the interaction between the operator and the robot systems and/or between the operator and the other elements of the workstation;
2. Maximize the operator wellbeing during the interaction with the robot and with other elements of the workstation in terms of physical and cognitive ergonomics;
3. Minimize the tasks time and costs for manual, robotic and collaborative tasks, especially for assembly;

3. General guidelines for the design of human-robot assembly workstations

Considering a CE approach, the design of workstation features and layout are strictly connected to the definition of other elements of HRI (see Fig.1). For this reason, the suggested guidelines necessarily integrate (and reflect to) other mutual considerations about assembly cycle, robot systems and product features. In addition, the need to develop human-centered and flexible applications entail the implementation of systems for real-time adjustment and optimization of workcell elements according to operator psychophysical features. Some examples could be adjustable workspaces as well as adaptable robot systems which are indispensable to ergonomically conform the work activities to the operators needs and wants.

3.1. Guidelines for human-robot assembly workstation design according to safety requirements

Following (Table 1), the main guidelines about the design of human-robot assembly workstation related to operator occupational safety are explained [5,6,7,8,9]. Considering that in case of collaborative assembly activities the main hazards are of mechanical type, the following guidelines are focused only on that kind of risks. For detailed instructions about the management of other occupational health and safety risks it is suggested to refer to specific directives, technical standards and deliverables.

Table 1. General guidelines about the design of human-robot assembly workstation related to operator occupational safety in terms of mechanical hazards [5,6,7,8,9]:

SAFETY	
1) Minimize specific mechanical hazards related to the entrapment of human body parts	
Motion planning	Set trajectories in such a way human body parts will not be easily trapped between the robot systems and the elements of the workstation Limit velocities of moving parts Limit momentum, mechanical power or energy as a function of masses and velocities Set safe virtual-plane-systems or space limiting functions which limit the robot to work in a defined volume Set collaborative robot speed limits for quasi-static contact Limit forces or torques of robot systems (including the end-effector) via SW Use safety-rated soft axis (implemented via SW)
Robot systems	Increase the contact surface area (round edges and corners; provide smooth surfaces; provide compliant surfaces) Manage energy absorption, enlarge energy transfer time or reduce impact forces (provide padding, cushioning or deformable components) Limit momentum, mechanical power or energy as a function of masses and velocities Use sensing to anticipate or detect contact (e.g. proximity or contact detection to reduce quasi-static forces) Design the end-effector to provide protection from hazards associated with the workpiece Limit forces or torques of robot systems (including the end-effector) via HW Prevent trap due to the moving cables of the robot systems Prevent trap due to exposed parts of the robot systems
WS elements	Use sensing to anticipate or detect contact (e.g. proximity or contact detection to reduce quasi-static forces) Highlight objects and obstacles into the workspace Prevent trap due to the exposed parts of the workstation elements
Organizational measures	Signal/highlight robot systems motion Signal the transition between collaborative operations and other kind of operations Monitor robot systems performance Set access routes (e.g. paths taken by operators, material movement to the collaborative workspace)
2) Minimize specific mechanical hazards related to collisions with human body parts	
Motion planning	Set trajectories in such a way human body parts will not be easily hit by the robot systems Set trajectories in such a way the energy exchange which can occur during unexpected collisions will be minimized Limit velocities of moving parts Limit momentum, mechanical power or energy as a function of masses and velocities Set safe virtual-plane-systems or space limiting functions which limit the robot to work in a defined volume Set collaborative robot speeds limit for transient contact Limit forces or torques of robot systems (including the end-effector) via SW Use safety-rated soft axis (implemented via SW) Use safety-rated monitored stop function
Robot systems	Increase the contact surface area (round edges and corners; provide smooth surfaces; provide compliant surfaces) Manage energy absorption, enlarge energy transfer time or reduce impact forces (provide padding, cushioning, deformable components or safety-rated soft axis) Limit moving masses Limit momentum, mechanical power or energy as a function of masses and velocities Design the end-effector to provide protection from hazards associated with the workpiece Limit forces or torques of robot systems (including the end-effector) via HW
WS elements	Increase the contact surface area (round edges and corners; provide smooth surfaces; provide compliant surfaces) Manage energy absorption, enlarge energy transfer time or reduce impact forces (provide padding, cushioning or deformable components)
Organizational measures	Signal/highlight robot systems motion Signal the transition between collaborative operations and other kind of operations Monitor robot systems performance Set access routes (e.g. paths taken by operators, material movement to the collaborative workspace)
3) Minimize specific mechanical hazards related to robot system parts falling	
Motion planning	Set trajectories in such a way a potential parts falling will limit the collision damages Limit velocities of moving parts Set safe virtual-plane-systems or space limiting functions which limit the robot to work in a defined volume
Robot systems	Limit moving masses Design the end-effector to provide protection from hazards associated with the workpiece
Organizational measures	Signal robot systems motion Monitor robot systems performance Set access routes (e.g. paths taken by operators, material movement to the collaborative workspace)
Robot systems = robot arm, end effector, controller, inherent sensors, (eventually) manipulated workpiece and in general everything is composing the robot system **Workstation elements** = devices, supports, equipment, workpieces and in general everything is present in the workspace which has to be manipulated by the operator or by the robot during the activities	

3.2. Guidelines for human-robot assembly workstation design according to physical ergonomics requirements

Following (Table 2), the main guidelines about the design of human-robot assembly workstation related to operator physical ergonomics are explained [10].

Table 2. General guidelines about the design of human-robot assembly workstation related to operator physical ergonomics [10]:

PHYSICAL ERGONOMICS	
1) Minimize the bio-mechanical overload of upper limbs related to repetitive tasks	
Motion planning	Avoid HRIs which require the use of upper limbs for long time during the assembly
	Avoid HRIs which require the elbows position above the shoulder level for quite all the time during the assembly
	Avoid HRIs which require the use of moderate and continuous force during the assembly
	Avoid HRIs which require force peaks during the assembly
	Avoid HRIs which require the need of grasping using the fingers tips (all kinds) for quite all the time during the assembly
	Avoid HRIs which require high frequency and similar movements of upper limbs during the assembly
Workstation elements	Avoid workspaces/workstation elements which require the use of upper limbs for long time during the assembly
	Avoid workspaces/workstation elements which require the elbows position above the shoulder level for quite all the time during the assembly
	Avoid workspaces/workstation elements which require the use of moderate and continuous force during the assembly
	Avoid workspaces/workstation elements which require force peaks during the assembly
	Avoid workspaces/workstation elements which require the need of grasping using the fingers tips (all kinds) for quite all the time during the assembly
	Avoid workspaces/workstation elements which require high frequency and similar movements of upper limbs during the assembly
2) Minimize the bio-mechanical overload of whole body related to manual lifting/lowering of objects	
Motion planning	Avoid HRIs which require to maintain the workstation elements far to the body during the assembly
	Avoid HRIs which require a vertical displacement outside the range between hips and shoulders during the assembly
	Avoid HRIs which require frequent body movements during the assembly
Workstation elements	Reduce the weight and/or support heavy equipment, devices and, in general, every workstation elements manipulated by the operators
	Avoid workspaces which require to maintain the workstation elements far to the body during the assembly
	Avoid workspaces which require a vertical displacement of workstation elements outside the range between hips and shoulders during the assembly
	Avoid workspaces which require frequent body movements for the management of workstation elements during the assembly
3) Minimize the bio-mechanical overload of head/neck/trunk/upper or lower limbs related to static or awkward working postures	
Motion planning	Avoid HRIs which require an asymmetric posture of booth neck and trunk during the assembly
	Avoid HRIs which require unsupported trunk backward inclination or harsh flexion during the assembly
	Avoid HRIs which require neck extension or hash flexion during the assembly
	Avoid HRIs which require unsupported head backward inclination or harsh inclination during the assembly
	Avoid HRIs which require a convex spinal curvature (if sitting) during the assembly
	Avoid HRIs which require awkward upper arm postures during the assembly
	Avoid HRIs which require raised shoulder during the assembly
	Avoid HRIs which require unsupported upper arm elevation during the assembly
	Avoid HRIs which require extreme elbow flexion/extension AND extreme forearm rotation during the assembly
	Avoid HRIs which require extreme wrist deviation during the assembly
	Avoid HRIs which require extreme knee flexion during the assembly
	Avoid HRIs which require knee not flexed in standing postures during the assembly
	Avoid HRIs which require not-neutral ankle position during the assembly
	Avoid HRIs which require kneeling or crouching during the assembly
	Avoid HRIs which require very high knee angle (if sitting) during the assembly
Workstation elements	Avoid workspaces/workstation elements which require an asymmetric posture of booth neck and trunk during the assembly
	Avoid workspaces/workstation elements which require unsupported trunk backward inclination or harsh flexion during the assembly
	Avoid workspaces/workstation elements which require neck extension or harsh flexion during the assembly
	Avoid workspaces/workstation elements which require unsupported head backward inclination or harsh inclination during the assembly
	Avoid workspaces/workstation elements which require a convex spinal curvature (if sitting) during the assembly
	Avoid workspaces/workstation elements which require awkward upper arm postures during the assembly
	Avoid workspaces/workstation elements which require raised shoulder during the assembly
	Avoid workspaces/workstation elements which require unsupported upper arm elevation during the assembly
	Avoid workspaces/workstation elements which require extreme elbow flexion/extension AND extreme forearm rotation during the assembly
	Avoid workspaces/workstation elements which require extreme wrist deviation during the assembly
	Avoid workspaces/workstation elements which require extreme knee flexion during the assembly
	Avoid workspaces/workstation elements which require knee in standing postures during the assembly
	Avoid workspaces/workstation elements which require not-neutral ankle position during the assembly
	Avoid workspaces/workstation elements which require kneeling or crouching during the assembly
	Avoid workspaces/workstation elements which require very high knee angle (if sitting) during the assembly

Robot systems = robot arm, end effector, controller, inherent sensors, (eventually) manipulated workpiece and in general everything is composing the robot system
Workstation elements = devices, supports, equipment, workpieces and in general everything is present in the workspace which has to be manipulated by the operator or by the robot during the activities

3.3. Guidelines for human-robot assembly workstation design according to cognitive ergonomics requirements

Following (Table 3), the main guidelines about the design of human-robot assembly workstation related to operator cognitive ergonomics are explained [11,12,13,14,15,16,17,18].

Table 3. General guidelines about the design of human-robot assembly workstation related to operator cognitive ergonomics [11,12,13,14,15,16,17,18]:

COGNITIVE ERGONOMICS	
Maximize operator psychological wellbeing and satisfaction	
Motion planning	Implement smooth trajectories (which can be assimilate to natural human-arm motions)
	Implement swing trajectories (not continuously straight)
	Avoid high speed motions
	Implement human-aware motion planning
Robot system	Use the lowest possible robot size

Workstation elements	Make elements well identifiable (highlight them, make them well visible, provide visual discrimination by size, color, texture, provide visual or auditory feedbacks) Make elements well distinguishable (highlight them, make them well visible, provide tactile discrimination by size, texture, provide visual or auditory feedbacks) Make the work intuitive (support the formation of a mental model, reduce the choice reaction time, facilitate the leaning transfer, promote similarity)
Organizational measures	Inform operators about the robot speed Involve operators into the definition of layout and work activities Avoid misalignment in operator and robot use of production resources (avoid inefficiency) Make the work intuitive (support the formation of a mental model, reduce the choice reaction time, facilitate the leaning transfer, promote similarity)
Robot systems = robot arm, end effector, controller, inherent sensors, (eventually) manipulated workpiece and in general everything is composing the robot system **Workstation elements** = devices, supports, equipment, workpieces and in general everything is present in the workspace which has to be manipulated by the operator or by the robot during the activities	

3.4. Guidelines for human-robot assembly workstation design according to assembly efficiency requirements

Following (Table 4), the main guidelines about the design of human-robot assembly workstation related to manual and robotic assembly efficiency are explained [19, 20, 21, 22, 23].

Table 4. General guidelines about the design of human-robot assembly workstation related to manual and robotic assembly efficiency [19, 20, 21, 22, 23]:

ASSEMBLY EFFICIENCY	
Maximize the efficiency of manual and robot assembly activities	
Workstation elements	Design workspaces in such a way the workstation elements are easily recognizable by an automatic vision system and by operators Design workstation elements in such a way they can be managed using the minimum number of robot systems tools Design workstation elements and workspaces by promoting standardization Design workspaces and workstation elements in such a way they can be easily fed, manipulated and stored by booth operators and robots Design workstation elements in such a way they provide an easy-to-reach and a free-from-obstacles access to assembly areas booth for operators and robots Design workstation elements in such a way they avoid the need of workpieces reorientations, adjustments, re-manipulation during the assembly activities Design workstation elements which are able to properly and efficaciously support the assembly activities booth for operators and robots
Robot systems = robot arm, end effector, controller, inherent sensors, (eventually) manipulated workpiece and in general everything is composing the robot system **Workstation elements** = devices, supports, equipment, workpieces and in general everything is present in the workspace which has to be manipulated by the operator during the activities	

4. Conclusions

In this paper, a collection and classification of prerequisites and design guidelines for the implementation of safe, human-centered and efficient human-robot assembly workstations are developed starting from international standards, research works and real use cases. This work will support the future development of an easy methodology for the evaluation of the existing applications as well as of new design ideas based on the fulfillment of different parameters contained into a check list. From the occupational health and safety point of view, this check list will also provide a first and general feedback about the compliance with some part of the mandatory Machinery Directive essential requirements. This has to be added with other requirements (for example for product design – see Fig. 1 concepts) in order to develop a general and complete list of guidelines for a proper development of industrial collaborative application by considering the product and process integration.. Some of the references used for the development of the abovementioned guidelines are numerous, easy to find and detailed while others are not. This condition underlines that there are topics related to industrial HRI which are more structured and attractive than others.
For example, the mechanical hazard part is explained by different international technical documents while the cognitive aspects are much more at a research and embryonic level. This situation underlain a certain unbalance between the development of different topics which theoretically are of the same level of importance (especially in case of occupational safety and ergonomics, which are booth essential and equally-important requirements to be necessary satisfied according to the Machinery Directive [24] indications).

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