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Risk Assessment for Collaborative Operation: A Case Study on Hand-Guided Industrial Robots

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Abstract

Risk assessment is a systematic and iterative process, which involves risk analysis, where probable hazards are identified, and then corresponding risks are evaluated along with solutions to mitigate the effect of these risks. In this article, the outcome of a risk assessment process will be detailed, where a large industrial robot is used as an intelligent and flexible lifting tool that can aid operators in assembly tasks. The realization of a collaborative assembly station has several benefits, such as increased productivity and improved ergonomic work environment. The article will detail the design of the layout of a collaborative assembly workstation, which takes into account the safety and productivity concerns of automotive assembly plants. The hazards associated with hand-guided collaborative operations will also be presented.

Keywords: hand-guided robots, industrial system safety, collaborative operations, human-robot collaboration, risk assessment, hazards

1. Introduction

In a manufacturing context, collaborative operations refer to specific applications where operators and robots share a common workspace [1, 2]. This allows operators and industrial robots to share assembly tasks within the pre-defined workspace—referred to as collaborative workspace—and this ability to work collaboratively is expected to improve productivity as well as the working environment of the operator [3].

As pointed out by Marvel et al. [1], collaborative operation implies that there is a higher probability for occurrence of hazardous situations due to close proximity of humans and industrial

robots. The hazardous situations can lead to serious injury and, therefore, safety needs to be guaranteed while developing collaborative applications [4].

ISO 10218-1 [5] and ISO 10218-2 [6] are international standards aimed at specifying requirements for safety on the design of industrial robots and robotic systems, respectively. They recognize collaborative applications and list four specific types of collaborative operations, namely (1) safety-rated monitored stop, (2) hand-guiding, (3) speed and separation monitoring, and (4) power and force limiting that can be implemented either individually or as a combination of one or more types.

As industrial robots and robotic systems are designed and integrated into specific manufacturing applications, the safety standards state that a risk assessment needs to be conducted is to ensure safe and reliable operations. Risk assessment, as standardized in ISO 12100 [7], is a detailed and iterative process of (1) risk analysis followed by (2) risk evaluation. The safety standards also state that the effect of residual risks needs to be eliminated or mitigated through appropriate risk reduction measures. The goal of a risk assessment program is to ensure that operators, equipment as well as the environment are protected.

As pointed out by Clifton and Ericson [8], hazard identification is a critical step, where the aim is the cognitive process of hazard recognition, whereas the solutions to mitigate the risks are relatively straightforward. Etherton et al. noted that designers lack a database of known hazards during innovation and design stages [9]. The robot safety standards (ISO 10218-1 [5] and ISO 10218-2 [6]) also have tabulated a list of significant hazards whose purpose is to inform risk assessors of probable inherent dangers associated with robot and robotic systems. Therefore, a case study [10] is used to investigate the characteristics of hazards and the associated risks that are relevant for collaborative operation. The study is focused on a collaborative assembly station, where large industrial robots and operators are to share a common workspace enabled through the application of a systematic and standardized risk assessment process followed by risk reduction measures.

This article is structured as follows: in Section 2, an overall description of the methodology used to conduct the research will be presented along with limitations; Section 3 will detail theoretical background; and Section 4 will present the results of the article followed by discussion of the result and conclude with remarks on future work.

1.1. Background

Recently, there have been many technological advances within the areas of robot control which aims to solve perceived issues associated with robot safety [11]. A safe collaborative assembly cell, where operators and industrial robots collaborate to complete assembly tasks, is seen as an important technological solution for several reasons including (1) ability to adapt to market fluctuations and trends [12]. (2) Have the possibility to decrease takt time [13, 14]. (3) Improving working environment by decreasing the ergonomic load of the operator [15].

An automotive assembly plant is typically separated into three units: (1) the highly automated body-in-white unit where industrial robots are used to weld sheet metal parts that form the chassis; (2) the body painting unit and (3) the final assembly unit where various components

of an automotive are assembled sequentially. The final assembly plants within the automotive industry can be characterized as:

1. having a high production rate, where the capacity of the plant can vary significantly depending on several factors, such as variant, plant location, etc.

2. being dependent on manual labor as the nature of assembly tasks require highly dexterous motion with good hand-eye coordination along with general decision-making skills.

Though, operators are often aided by powered tools to carry out assembly tasks such as pneumatic nut-runners as well as lifting tools, there is a need to improve the ergonomics of their work environment. As pointed by Ore et al. [15], there is demonstrable potential for collaborative operations to aid operators in various tasks including assembly and quality control.

Earlier attempts at introducing automation devices, such as cobots [13, 16], have resulted in custom machinery that functions as ergonomic support. Recently, industrial robots specifically designed for collaboration such as UR10 [17] and KUKA iiwa [18] are available that can be characterized as: (1) having the ability to detect collisions with any part of the robot structure; and (2) having the ability to carry smaller load and shorter reach compared to traditional industrial robots. This feature coupled with the ability to detect collisions fulfills the condition for power and force limiting.

Industrial robots that does not have power and force limiting feature, such as KUKA KR210 [18] or the ABB IRB 6600 [19], have traditionally been used within fenced workstations. In order to enter a robot workspace, the operator was required to deliberately open a gate, which is monitored by a safety device that stops all robot and manufacturing operations within the workstation. As mentioned before, the purpose of the research project was to explore collaborative operations where traditional industry robots are employed for assembly tasks. These robots have the capacity to carry heavy loads with long reach that can be effective for various assembly tasks. However, these advantages correspond to an inherent source of hazard that needs to be understood and managed with appropriate safety focused solutions.

2. Working methodology

To take advantage of the physical performance characteristics of large industrial robots along with the advances in sensor and control technologies, a research project ToMM [20] comprising of members representing the automotive industry, research, and academic institutions were tasked with understanding and specifying industry-relevant safety requirements for collaborative operations.

2.1. Industrial relevance

The requirements for safety that are relevant for the manufacturing industry are detailed in various standards such as ISO EN 12100 and ISO EN 10218 (parts 1 and 2) which are maintained

by various organizations such as International Organization for Standardization (ISO [21]) and International Electrotechnical Commission (IEC [22]). Though these organizations do not have the authority to enforce the standards, a legislatory body such as the European Union, through the EU Machinery directive mandates compliance with normative standards [23] which are prefixed with an EN before their reference number.

2.2. Problem study and data collection

Objective of the research was to understand the safety requirements for high-volume assembly stations when industrial robots are to be used in a collaborative manner. A case-based approach [10] was followed, where the initial study was focused on an assembly station where a heavy engine component is assembled on an engine block. To gain a better understanding and knowledge of the case study, the following methods were employed:

1. Regular meeting in order to have detailed discussion with engineers and line managers at the assembly plant [24].

2. Visits to the plant allowed the researchers to directly observe the functioning of the station. This also enabled the researchers to have informal interviews with line workers regarding the assembly tasks as well as the working environment.

3. The researchers participated in the assembly process, guided by the operators, allowed the researchers to gain intuitive understanding of the nature of the task.

4. Literature sourced from academia, books as well as documentation from various industrial equipment manufactures were reviewed.

2.3. Integrating safety in early design phase

Introduction of a robot into a manual assembly cell might lead to unforeseen hazards whose potential to cause harm needs to be eliminated or minimized. The machinery safety standard [7] suggests the practice of conducting risk assessment followed by risk reduction measures to ensure the safety of the operator as well as other manufacturing processes. The risk assessment process is iterative that concludes when all probable hazards have been identified along with solutions to mitigate the effects of these hazards have been implemented. This process is usually carried out through a safety program and can be documented according to [25].

Figure 1 depicts an overview of the safety-focused design strategy employed during the research and development phase. The case study was analyzed to understand the benefits of collaborative operations done through a conceptual study, where the overall robot, operator, and collaborative tasks were specified. Employing the results of the conceptual study, the risk assessment methodology followed by risk reduction was carried out where each phase was supported by the use of demonstrators. Björnsson [26] and Jonsson [27] have elaborated the principles of demonstrator-based design along with their perceived benefits and this methodology has been employed in this research work within the context of safety for collaborative operations.
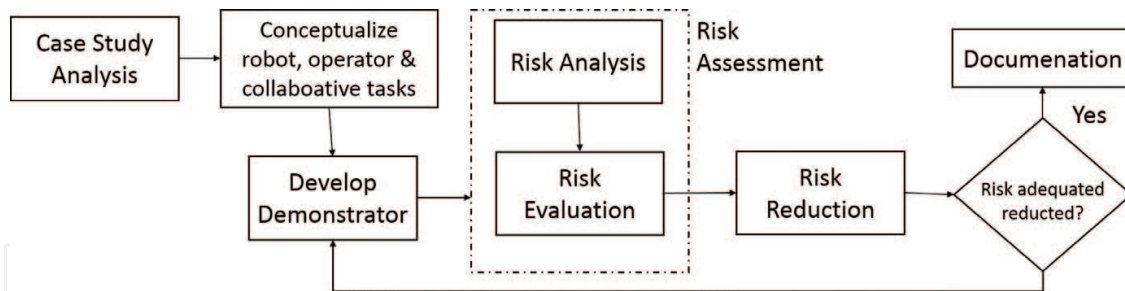
Figure 1. Overview of the demonstrator-based design methodology employed to ensure a safe collaborative workstation.

3. Theoretical background

In this section, beginning with an overview of industrial robots, concepts from hazard theory, industrial system safety and reliability, and task-based risk assessment methodology will be detailed.

## 3.1. Industrial robotic system and collaborative operations

An industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications [28]. **Figure 2(A)** shows an illustration of an articulated six-axis manipulator along with the control cabinet and a teach pendant. The control cabinet houses various control equipment such as motor controller, input/output modules, network interfaces, etc.

The teach pendant is used to program the robot, where each line of code establish the robot pose—in terms of coordinates in x, y, z and angles A, B, C—which when executed allow the robot to complete a task. This method of programming is referred to as position control, where individual robot poses are explicitly hard coded. In contrast to position control, sensor-based control allows motion control to be regulated by sensor values. Examples of sensors include vision, force and torque, etc.

On a manufacturing line, robots can be programmed to move at high speed undertaking repetitive tasks. This mode of operation is referred to as automatic mode, and allows the robot controller to execute the program in a loop, provided all safety functions are active. Additionally, ISO 10218-1 [5] has defined manual reduced-speed to allows safe programming and testing of the intended function of the robotic system, where the speed is limited to 250 mm/s at the tool center point. The manual high-speed allows the robot to be moved at high speed, provided all safety functions are activate and this mode is used for verification of the intended function.

The workspace within the robotic station where robots run in automatic mode is termed Robot Workspace (see **Figure 2(B)**). In collaborative operations, where operators and robots can share a workspace, a clearly defined Collaborative Workspace is suggested by [29]. Though the robot can be moved in automatic mode within the collaborative workspace, the speed of the robot is limited [29] and is determined during risk assessment.
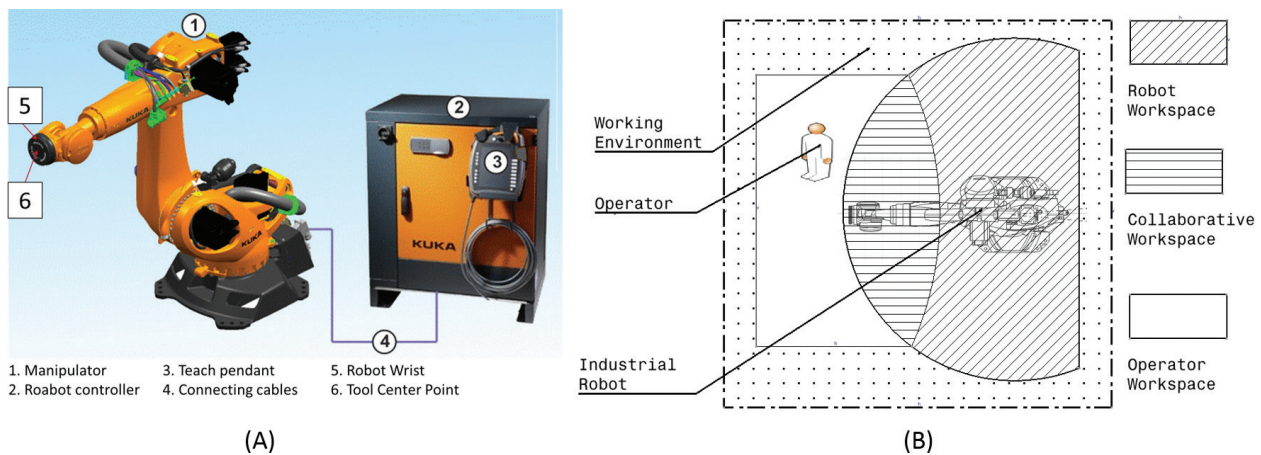
Figure 2. (A) An example of a manipulator along with the control box and the teach pendant. Examples include KUKA KR-210 [18] and ABB IR 6620 [19]. (B) Illustrates the interaction between the three participants of a collaborative assembly cell within their corresponding workspaces [3].

Robot safety standards recognize the implementation of one or more of the following four different modes of collaborative operation:

1. Safety-rated monitored stop stipulates that the robot ceases its motion with a category stop 2 when the operator enters the collaborative workspace. In a category stop 2, the robot can decelerate to a stop in a controlled manner.

2. Hand-guiding allows the operator to send position commands to the robot with the help of a hand-guiding tool attached at or close to the end-effector.

3. Speed and separation monitoring allows the operator and the robot to move concurrently in the same workspace provided that there is a safe separation distance between them which is greater than the prescribed protective separation distance determined during risk assessment.

4. Power and force limiting operation refers to robots that are designed to be intrinsically safe and allows contact with the operator provided it does not exert force (either quasi-static or transient contact) larger than a prescribed threshold limit.

3.2. Robotic system safety and reliability

An industrial robot normally functions as part of an integrated manufacturing system (IMS) where multiple subsystems that perform different functions operate cohesively. As noted by Levenson (page 14 [30]), safety is a system property (not a component property) and needs to be controlled at the system level. This implies that safety as a property needs to be considered at early design phases, which Ericson (page 34 [8]) refers to as CD-HAT or Conceptual Design Hazard Analysis Type. CD-HAT is the first seven types of hazard analysis types, which needs to be considered during various design phases in order to avoid costly design rework.

To realize a functional IMS, a coordinated effort in the form of a system safety program (SSP [8]) which involve participants with various levels of involvement (such as operators, maintenance, line managers, etc.) are carried out. Risk assessment and risk reduction processes are conducted in conjecture with the development of an IMS, in order to promote safety, during development, commissioning, maintenance, upgradation, and finally decommissioning.

3.2.1. Functional safety and sensitive protective equipment (SPE)

Functional safety refers to the use of sensors to monitor for hazardous situations and take evasive actions upon detection of an imminent hazard. These sensors are referred to as sensitive protective equipment (SPE) and the selection, positioning, configuration, and commissioning of equipment have been standardized and detailed in IEC 62046 [31]. IEC 62046 defines the performance requirements for this equipment and as stated by Marvel and Norcross [32], when triggered, these sensors use electrical safety signals to trigger safety function of the system. They include provisions for two specific types: (1) electro-sensitive protective equipment (ESPE) and (2) pressure-sensitive protective equipment (PSPE). These are to be used for the detection of the presence of human beings and can be used as part of the safety-related system [31].

Electro-sensitive protective equipment (ESPE) uses optical, microwaves, and passive infrared techniques to detect operators entering a hazard zone. That is, unlike physical fence, where the operators and the machinery are physically separated, ESPE relies on the operators to enter a specific zone for the sensor to be triggered. Examples include laser curtains [33], laser scanners [34], and vision-based safety systems such as the SafetyEye [35].

Pressure-sensitive protective equipment (PSPE) has been standardized in parts 1–3 of ISO13856, and works on the principle of an operator physically engaging a specific part of the workstation. These include: (1) ISO 13856-1—pressure sensitive mats and floors [36]; (2) ISO 13856-2—pressure sensitive bars, edges [37]. (3) ISO 13856-3—bumpers, plates, wires, and similar devices [38].

3.2.2. System reliability

Successful robotic systems are both safe to use and reliable in operation. In an integrated manufacturing system (IMS), reliability is the probability that a component of the IMS will perform its intended function under pre-specified conditions [39]. One measure of reliability is MTTF (mean time to failure) and ranges of this measure has been standardized into five discrete level levels or performance levels (PL) ranging from a to e. For example, PL = d refers to a $10^{-6} >$ MTTF $\geq 10^{-7}$, which is the required performance level with a category structure 3 ISO 10218-2 (page 10, Section 5.2.2 [6]). That is, in order to be viable to the industry, the final design of the robotic system should reach or exceed the minimum required performance level.

3.3. Hazard theory: hazards, risks, and accidents

Ericson [8] states that a mishap or an accident is an event which occurs when a hazard, or more specifically hazardous element, is actuated upon by an initiating mechanism. That is, a

hazard is a pre-requisite for an accident to occur and is defined as a potential source of harm [7] and is composed of three basic components: (1) hazardous element (HE), (2) initiating mechanism (IM), and (3) target/threat (T/T).

A hazardous element is a resource that has the potential to create a hazard. A target/threat is the person or the equipment directly affected when the hazardous element is activated by an initiating mechanism. These three components, when combined together, can be referred to as a hazard (see **Figure 3(A)**) and are essential components for it to exist. Based on these definitions, if any of the three components are removed or eliminated, by any means (see Section 3.4.2), it is possible to eliminate or reduce the effect of the hazard.

To better illustrate these concepts, consider the fatal accident that took place on July 21, 1984, where an experienced operator entered a robotic workstation while the robot was in automatic mode (see **Figure 3(B)**). The robot was programmed to grasp a die-cast part, dip the part in a quenching tank and place it on an automatic trimming machine. According to Lee et al. [40], the operator was found pinned between the robot and a safety-pole by another operator of an adjacent die-cast station who became curious after hearing the hissing noise of the air-hose for 10–15 min. The function of the safety pole was to limit robot motion and together with the robot-arm can be considered to be a hazardous element. The hazard was initiated by the operator who intentionally entered the workstation either by jumping over the rails or through a 19-inch unguarded spacing and caused the accident. The operator was the target of this unfortunate accident and was pronounced dead after 5 days of the accident.

A hazard is designed into a system [8, 30] and for accident to occur depends on two factors: (1) unique set of hazard components and (2) accident risk presented by the hazard components, where risk is defined

$$Risk \ = \ Probability \ \mathrm{x} \ Severity \tag{1}$$
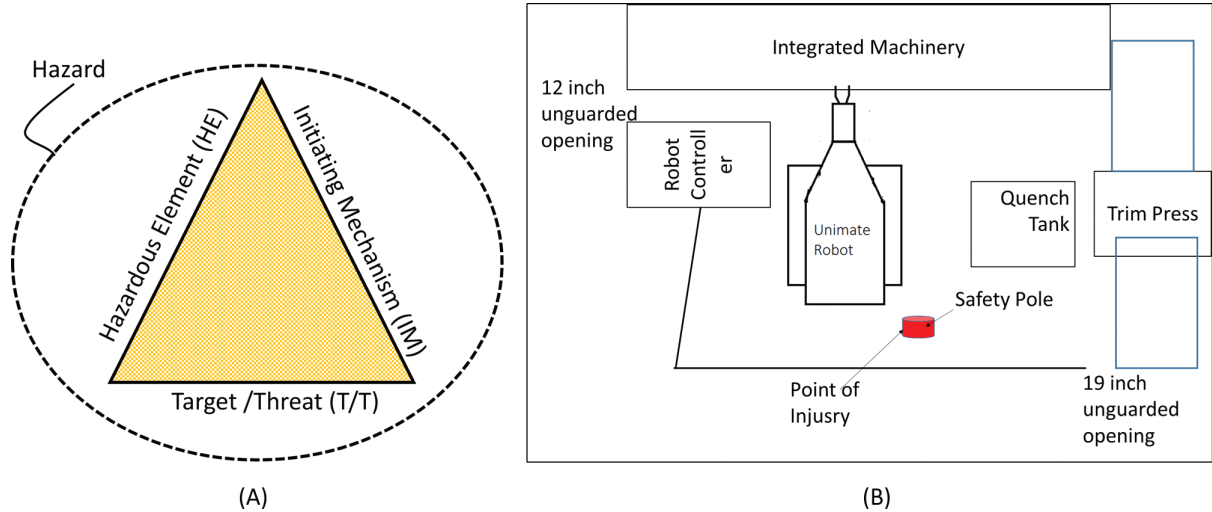
Figure 3. (A) The hazard triangle where the three components of hazards—hazardous element, initiating mechanism, and target/threat—are essential and required for the hazard to exist (adapted from page 17 [8]). (B) Shows the layout of the robotic workstation where a fatal accident took place on July 21, 1984 [40].

Ericson notes that a good hazard description can support the risk assessment team to better understand the problem and therefore can enable them to make better judgments (e.g., understanding the severity of the hazard), and therefore suggest that the a good hazard description needs to contain the three hazard components.

3.4. Task-based risk assessment and risk reduction

Risk assessment is a general methodology where the scope is to analyze and evaluate risks associated with complex system. Various industries have specific methodologies with the same objective. Etherton has summarized a critical review of various risk assessment methodologies for machine safety in [41]. According to ISO 12100, risk assessment (referred to as MSRA—machine safety risk assessment [41]) is an iterative process which involves two sequential steps: (1) risk analysis and (2) risk evaluation. ISO 12100 suggests that if risks are deemed serious, measures should be taken to either eliminate or mitigate the effects of the risks through risk reduction as depicted in **Figure (4)**.

3.4.1. Risk analysis and risk evaluation

Within the context of machine safety, risk analysis begins with identifying the limits of machinery, where the limits in terms of space, use, time are identified and specified. Within this boundary, activities focused on identifying hazards are undertaken. The preferred context for identifying hazards for robotics systems is task-based, where he tasks that needs to be undertaken during various phases of operations are first specified. Then the risk assessors specify the hazards associated with each tasks. Hazard identification is a critical step and ISO 10218-1 [5] and ISO 10218-2 [6] tabulates significant hazards associated with robotic systems. However, they do not explicitly state the hazards associated with collaborative operations.

Risk evaluation is based on a systematic metrics where severity of injury, exposure to hazard and avoidance of hazard are used to evaluate the hazard (see page 9, RIA TR R15.306-2014 [25]). The evaluation results in specifying the risk level in terms of negligible, low, medium-high, and very-high, and determine risk reduction measures to be employed. To support the activities associated with risk assessment, ISO TR 15066 [29] details information required to conduct risk assessment specifically for collaborative applications.

3.4.2. Risk reduction

When risks are deemed serious, the methodology demands measures to eliminate and/or mitigate the risks. The designers have a hierarchical methodology that can be employed to varying degree depending on the risks that have to be managed. The three hierarchical methods allow the designers to optimize the design and can choose either one or a combination of the methods to sufficiently eliminate/mitigate the risks. They are: (1) inherently safe design measures; (2) safeguarding and/or complementary protective measures; and (3) information for use.
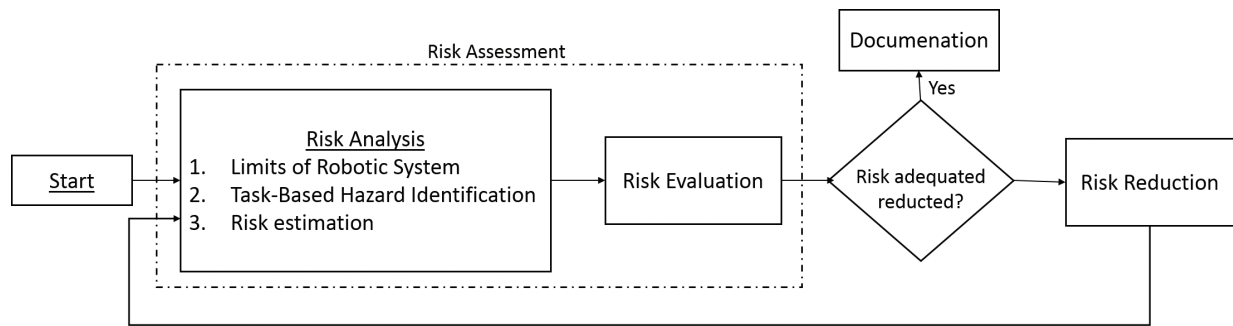
Figure 4. An overview of the task-based risk assessment methodology.

4. Result: demonstrator for a safe hand-guided collaborative operation

In this section, the development and functioning of a safe assembly station will be detailed, where a large industrial robot is used in a hand-guided collaborative operation. In order to understand potential benefits with hand-guided industrial robots, an automotive assembly station will be presented as a case study in Section 4.1. With the aim to improve the ergonomics of the assembly station and increase the productivity, the assembly tasks are conceptualized as robot, operator, and collaborative task where the collaborative task is the hand-guided operation and is described in Section 4.2. The results of the iterative risk assessment and risk reduction process (see Section 3.4) will be detailed in Section 4.3. The final layout and the task sequence will be detailed in Section 4.4, and **Table 1** will document the hazards that were identified during risk assessment that were used to improve the safety features of the assembly cell.

4.1. Case study: manual assembly of a flywheel housing cover

The assembly task is to install a flywheel housing cover (FWC) on the engine block with an intermediate step between the picking of the FWC from the material rack and securing it on the engine block with fasteners. The assembly of FWC, which weighs 20 kg, is a manual operation and these tasks are carried out by one or more operators (see **Figure 5(A)**) and can be described as follows:

1. An operator picks up the flywheel housing cover (FWC) with the aid of a lifting device from position P1. The covers are placed on a material rack and can contain upto three part variants.

2. This operator moves from position P1 to P2 by pushing the FWC and installs it on the machine (integrated machinery) where secondary operations will be performed.

3. After the secondary operation, the operator pushes the FWC to the engine housing (position P3). Here, the operator needs to align the flywheel housing cover with the engine block with the aid of guiding pins. After the two parts are aligned, the operator pushes the flywheel housing cover forward until the two parts are in contact. The operator must exert force to mate these two surfaces.

4. Then the operators begin to fasten the parts with several bolts with the help of two pneumatically powered devices. In order to keep low takt time, these tasks are done in parallel and require the participation of more than one operator.

No.	Hazard description	Hazardous element (HE)	Initiating mechanism (IM)	Target/threat (T/T)	Risk reduction measure
1.	The operator can accidentally enter robot workspace and collide with the robot moving at high speed	Fast moving robot	Operator is unaware of the system state	Operators	1. A light curtain to monitor the robot workspace. 2. A lamp to signal the system state
2.	In collaborative mode, sensor-guided motion is active. Robot motion can be triggered unintentionally resulting in unpredictable motion	Crushing	Operator accidentally activate the sensor,	Operator(s) and/or equipment(s)	An enabling device, when actuated, will start sensor-guided motion. An ergonomically designed enabling device can act as a hand-guiding tool
3.	The operator places their hands between the FWC and the engine, thereby crushing their hands	Crushing	Operator distracted due to assembly task	Operator	An enabling device can ensure that the operator's hands are at a predefined location.
4.	While aligning the pins with the holes, the operator can break the pins by moving vertically or horizontally	Imprecise hand-guided motion	Operator fails to keep steady motion	Operators	1. Vertical hand-guided motion needs to be eliminated. 2. Operator training
5.	The robot collides with an operator while being hand-guided by another operator	Collision	Designated operator is not aware of others in the vicinity	Operators	The designated operator has clear view of the station
6.	An operator accidentally engages mode-change button though the collaborative task is incomplete	Error in judgment of the operators	Engaging the mode-change button	Operator/ equipment	A button on the hand-guiding tool that the operator engages before exiting the workspace

Table 1. The table describes the hazards that were identified during the risk assessment process.

(A)   (B)   (C)
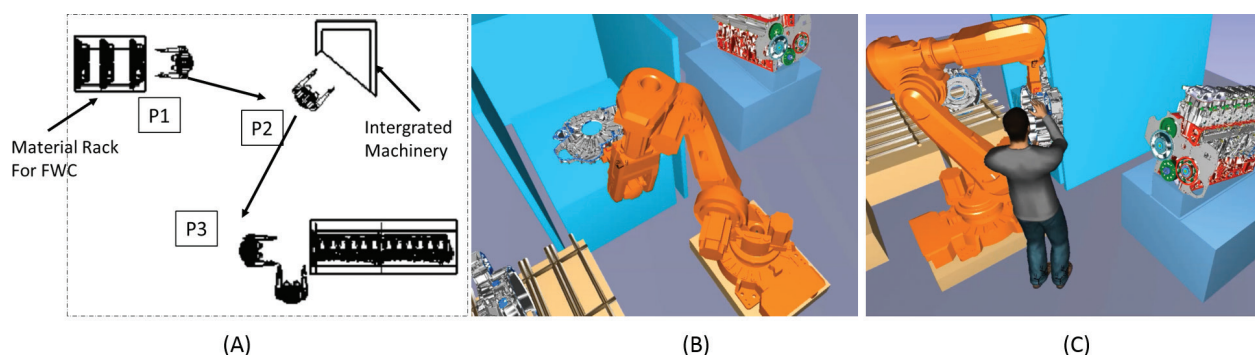
Figure 5. (A) Shows the manual workstation where several operators work together to assemble flywheel housing covers (FWC) on the engine block. (B) Shows the robot placing the FWC on the integrated machinery. (C) Shows the robot being hand-guided by an operator thereby reducing the ergonomic effort to position the flywheel housing cover on the engine block.

4.2. Task allocation and conceptual design of the hand-guiding tool

Figure 5(B) and **(C)**, shows ergonomic simulations reported by Ore et al. [15] and shows the operator being aided by an industrial robot to complete the task. The first two tasks can be

automated by the robot, i.e., picking the FWC from Position 1 and moving it to the integrated machine (position P2, **Figure 5(B)**). Then, the robot moves the FWC to the hand over position where the robot will come to a stop and signal to the operator that the collaborative mode is activated. This allows the operator to hand-guide the robot by grasping the FWC and directing the motion towards the engine block.
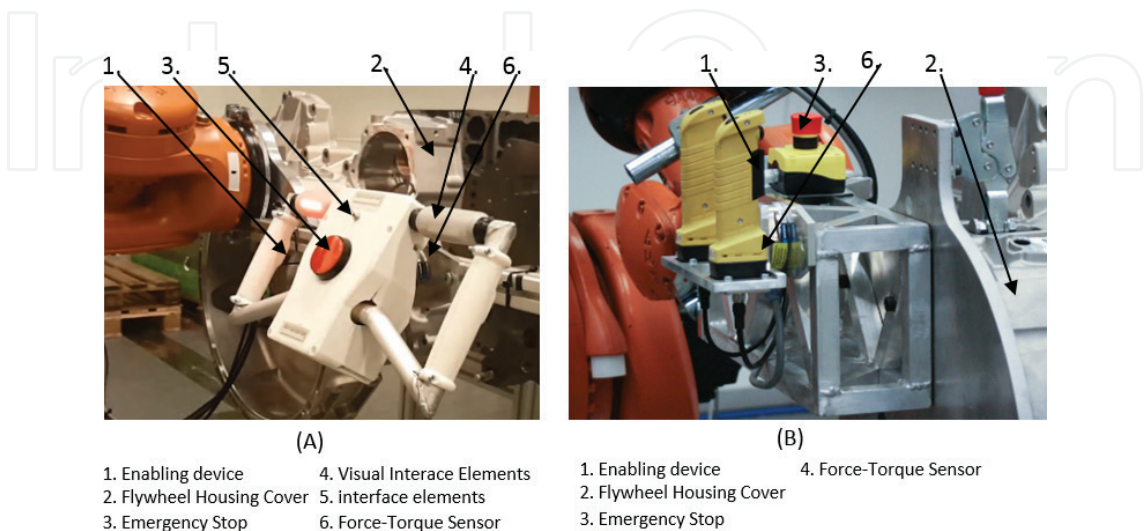
Once the motion of the robot is under human control, the operator can assemble the FWC onto the engine block and proceeds to secure it with bolts. After the bolts have been fastened, the operator then moves the robot back to the hand-over position and reactivates the automatic mode which starts the next cycle.

4.3. Safe hand-guiding in the collaborative workspace

The risk assessment identified several hazardous situations that can affect the safe functioning during the collaborative mode—that is when the operator goes into the workstation and hand-guides the robot to assemble the FWC—and has been tabulated in **Table 1**.

Figure 6(A) and **(B)** shows two versions of the end-effector that was developed to support hand-guided robotic assembly. The safety focused design of the hand-guiding tool shown in **Figure 6(A)** has been detailed by Gopinath et al. [42] where the interfaces are part of the end-effector. That is, in an open enclosure (without physical fences—not shown), the location for the interfaces and control devices would optimally be a design feature of the end-effector. However, risk assessment pointed out that an open enclosure might require the following safety measures:

1. The robot needs to be programmed to move at slow speed so that it can stop (in time) according to speed and separation monitoring mode of collaborative operation.

2. To implement speed and separation monitoring, a safety rated vision system might be probable solution. However, this may not be viable solution on the current factory floor.

(A)

1. Enabling device   4. Visual Interace Elements
2. Flywheel Housing Cover 5. interface elements
3. Emergency Stop   6. Force-Torque Sensor

(B)

1. Enabling device   4. Force-Torque Sensor
2. Flywheel Housing Cover
3. Emergency Stop

Figure 6. (A) and (B) are two versions of the end-effector that was prototyped to verify and validate the design.

The limited space, high volume and the nature of the hazards puts severe restriction on the type of safety solution that can be considered. An enclosed station is shown in **Figure 7**, where physical fences are being used as a safeguarding measure to limit personnel movement, thereby eliminating the possibility of operator accidently entering the robot workspace. The layout of this collaborative station has been detailed by Gopinath et al. [43] and in **Table 2**, a comparison of the design features has been discussed. The change from Design A to Design B was motivated by change in requirements namely:

1. A change in design that would allow the operator to visually align the pins on the engine block with the mating holes on the FWC.

2. A change in design to improve reliability as well as avoid tampering through the use of standardized components. Ensure that the operator feel safer during hand-guiding by ensuring that the robot arms are not close to the operator.

### 4.4. Demonstrator for a safe hand-guided collaborative assembly workstation

Figure 7 shows a picture of the demonstrator developed in a laboratory environment. Here, a KUKA KR-210 industrial robot is part of the robotic system where the safeguarding solutions include the use of physical fences as well as sensor-based solutions.

Figure 8 describes the sequence of task necessary to complete the assembly operations. These tasks have been separated into three, i.e., robot, operator, and collaborative tasks and can be described as follows:

1. The robot tasks, which are preprogramed tasks undertaken in automatic mode. When the robot tasks are completed, it is programmed to stop at the hand-over position.

2. The collaborative task which begins when the operators enters the monitored space and takes control of the robot using the hand-guiding device. The collaborative mode is complete when the operator returns the robot to the hand-over position and restarts the automatic mode.

3. The operator task is the fastening of the bolts required to secure the FWC to the engine block. The operators need to fasten several bolts and therefore use pneumatically powered tool (not shown here) to help them with this task.

4.4.1. Safeguarding

With an understanding that operators are any personnel within the vicinity of hazardous machinery [7], the physical fences can be used to ensure that they do not accidentally enter a hazardous zone. The design requirements stated that the engine block needs to be outside the enclosed zone, meant that the robot needs to move out of the fenced area during collaborative mode (see **Figure 8**). Therefore, the hand over position is located inside the enclosure and the assembly point is located outside of the enclosure and both these points are part of the collaborative workspace. The opening in the fences is monitored during automatic mode using laser curtains.
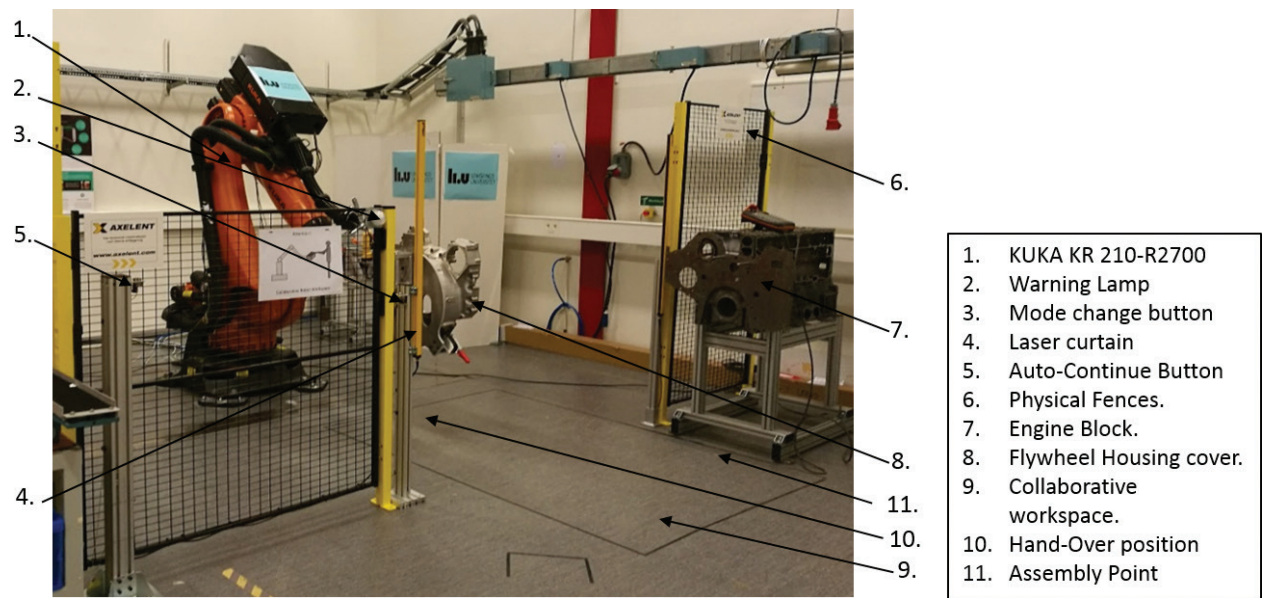
Figure 7. The layout of the physical demonstrator installed in a laboratory environment.

Design feature	Design A	Design B	Design evaluation
1. Orientation of the end-effector	End-effector is parallel to the robot wrist	End-effector is perpendicular to the robot wrist.	In design A, the last two links of the robot are close to the operator which might make the operators feel unsafe. Design B might allow for an overall safer design due to use of standardized components
2. Position of Flywheel housing cover (FWC)	The FWC is positioned left to the operator	The FWC is positioned in front of the operator	Design A requires more effort from the operator to align the locating pins (on the engine block) and the mating holes (on the FWC). The operator loses sight of the pins when the two parts are close to each other. In Design B, it is possible to align the two parts by visually aligning the outer edges
3. Location of Emergency stop	Good location and easy to actuate	Good location and easy to actuate	In design A, it was evaluated that the E-stop can be accidentally actuated which might lead to unproductive stops
4. Location of visual interfaces	Good location and visibility	No visual interfaces	Evaluation of design A resulted in the decision that interfaces need to be visible to all working within the vicinity
5. Location of physical interfaces	Good location with easy reach.	Minimal physical interfaces	Evaluation of design A resulted in the decision that interfaces are optimally placed outside the fences area
6. Overall ergonomic design	The handles are angled and is more comfortable	The distance between the handles is short	Designs A and B have good overall design. Design B uses standardized components. Design A employs softer materials and interfaces that are easily visible

Table 2. Feature comparison of two versions of the end-effector shown in **Figure 6(A)** and **(B)**.
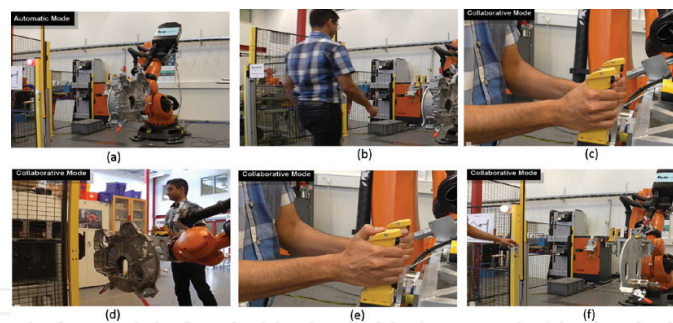
Figure 8. The figure describes the task sequence of the collaborative assembly station where an industrial robot is used as an intelligent and flexible lifting tool. The tasks are decomposed into three — Operator task (OT), Collaborative task (CT) and Robot task (RT) — which are detailed in **Table 3**.

4.4.2. Interfaces

During risk evaluation, the decision to have several interfaces was motivated. A single warning LED lamp (see **Figure 8**) can convey that when the robot has finished the preprogrammed task and waiting to be hand-guided. Additionally, the two physical buttons outside the enclosure has separate functions. The Auto-continue button allows the operator to let the robot continue in automatic mode if the laser curtains were accidentally triggered by an operator and this button is located where it is not easily reached. The second button is meant to start the next assembly cycle (see **Table 1**). **Table 1** (Nos. 2 and 3) motivates the use of enabling devices to trigger the sensor guided motion (see **Figure 6(B)**). The two enabling devices provide the following functions: (1) it acts as a hand-guiding tool that the operator can use to precisely maneuver the robot. (2) By specifying that the switches on the enabling device are engaged for hand-guiding motion, the operators hands are at a prespecified and safe location. (3) Additionally, by engaging the switch, the operator is deliberately changing the mode of the robot to collaborative-mode. This ensures that unintended motion of the robot is avoided.

Tasks	Task description
1. Robot task	The robot tasks are to pick up the flywheel housing cover, place the part on the fixture and when the secondary operators are completed, pick up the part and wait at the hand-over position. During this mode, the warning lamp is red, signaling automatic mode. The hand-over position is located inside the enclosed area and is monitored by laser curtains. The robot will stop if an operator accidentally enters this workspace and can be restarted by the auto-continue button (**Figure 7**)
2. Operator task	Enter collaborative space: When the warning lamp turns to green, the laser curtains are deactivated; the operator enters the collaborative workspace
3. Collaborative task	Engage enabling switch: the operator begins hand-guiding by engaging both the enabling switches simultaneously. This activates the sensor-guided motion and the operator can move the robot by applying force on the enabling device. If the operator releases the enabling switch, the motion is deactivated (see point 2 in **Table 1**). To reactivate motion, the operator engages both the enabling switches
4. Collaborative task	Hand-guide the robot: the operator moves the FWC from the hand-over position to the assembly point. Then removes the clamp and return the robot back to the hand-over position

Tasks	Task description
5. Collaborative task	Engage automatic mode: before going out of the assembly station, the operator needs to engage the three-button switch. This deliberate action signals to the robot that the collaborative task is complete
6. Robot task	The operator goes out and engages the mode-change button. Then, the following sequence of events is carried out: (1) laser curtains are activated, (2) warning lamp turns from green to red, and (3) the robot starts the next cycle

Table 3. The table articulates the sequence of tasks that were formulated during the risk assessment process.

5. Discussion

In this section, the discussion will be focused on the application of the risk assessment methodology and the hazards that were identified during this process.

5.1. Task-based risk assessment methodology

A risk assessment (RA) is done on a system that exists in a form that can function as a context within which hazards can be documented. In the case study, a force/torque sensor was used to hand-guide the robot and this technique was chosen at the conceptual stage. RA based on this technique led to decision of introducing enabling devices (No. 2 in **Table 1**) to ensure that, while the operator is hand guiding the robot, the hands are within a predetermined safe location and is engaged. Another industrially viable solution is the use of joysticks to hand-guide the robot but this option was not explored further during discussion as it might be less intuitive than force/torque based control. Regardless, it is implicit that the choice of technique poses its own hazardous situation and the risk assessors need a good understanding of the system boundary.

Additionally, during risk assessment, the failure of the various components was not considered explicitly. For example, what if laser curtains failed to function as intended? The explanation lies in the choice of components. As stated in Section 3.2.2, a robotic system to be considered reliable, the components must have a performance level PL = d, which implies a very low probability of failure. Most safety-equipment manufactures publish their MTTF values along with their performance levels and the intended use.

5.2. Hazards

The critical step in conducting risk assessment (RA) is hazard identification. In Section 3.3, a hazard was decomposed into three: (1) hazardous element (HE), (2) initiating mechanism (IM), and (3) target/threat (T/T). The three sides of the hazard triangle (Section 3.3) have lengths proportional to the degree with which these components can trigger the hazard and cause an accident. That is, if the length of IM side is much larger than the other two, then the most influencing factor to cause an accident is IM. The discussion on risk assessment (Section 3.4) stresses on eliminating/mitigating hazards which implies that the goal of risk assessment can

be understood as a method to reduce/remove one or more of the sides of the hazard triangle. Therefore, documenting the hazards in terms of its components might allow for simplified and straightforward downstream RA activities.

The hazards presented in **Table 1** can be summarized as follows: (1) the main source of hazardous element (HE) is slow/fast motion of the robot. (2) The initiating mechanism (IM) can be attributed to unintended actions by an operator. (3) The safety of the operator can be compromised and has the possibility to damage machinery and disrupt production. It can also be motivated, based on the presented case study, that through the use of systematic risk assessment process, hazards associated with collaborative motion can be identified and managed to an acceptable level of risk.

As noted by Eberts and Salvendy [44] and Parsons [45], human factors play a major role in robotic system safety. There are various parameters that can be used to better understand the effect of human behavior in system such as overloaded and/or underloaded working environment, perception of safety, etc. The risk assessors need to be aware of human tendencies and take into consideration while proposing safety solutions. Incidentally, in the fatal accident discussed in Section 3.3, perhaps the operator did not perceive the robot as a serious threat and referred to the robot as Robby [40].

In an automotive assembly plant, as the production volume is relatively high and requires collaborating with other operators, there is a higher probability for an operator to make errors. In **Table 1** (No. 6), a three-button switch was specified to ensure unintentional mode change of the robot. It is probable that an operator can accidentally engage the mode-change button (see **Figure 7**) while the robot is in collaborative mode or the hand-guiding operator did not intend the collaborative mode to be completed. In such a scenario, a robot operating in automatic mode was evaluated to have a high risk level, and therefore the decision was made to have a design change with an additional safety-interface—the three-button switch—that is accessible only to the hand-guiding operator.

Informal interviews suggested that the system should be inherently safe for the operators and that the task sequence—robot, operator, and collaborative tasks—should not demand constant monitoring by the operators as it might lead to increased stress. That is, operators should feel safe and in control and that the tasks should demand minimum attention and time.

6. Conclusion and future work

The article presents the results of a risk assessment program, where the objective was the development of an assembly workstation that involves the use of a large industrial robot in a hand-guiding collaborative operation. The collaborative workstation has been realized as a laboratory demonstrator, where the robot functions as an intelligent lifting device. That is, the tasks that can be automated have been tasked to the robot and these sequences of tasks are preprogrammed and run in automatic mode. During collaborative mode, operators are responsible for tasks that are cognitively demanding that require the skills and flexibility inherent to a human being. During this mode, the hand-guided robot carries the weight of the flywheel housing cover, thereby improving the ergonomics of the workstation.

In addition to the laboratory demonstrator, an analysis of the hazards pertinent to hand-guided collaborative operations has been presented. These hazards were identified during the risk assessment phase, where the hazardous element mainly stems from human error. The decisions taken during the risk reduction phase to eliminate or mitigate the risks associated with these hazards have also been presented.

The risk assessment was carried out through different phases, where physical demonstrators supported each phase of the process. The demonstrator-based approach allowed the researchers to have a common understanding of the nature of the system and the associated hazards. That is, it acted as platform for discussion. The laboratory workstation can act as a demonstration platform where operators and engineers can judge for themselves the advantage and disadvantages of collaborative operations. The demonstration activities can be beneficial to researchers as it can function as a feedback mechanism with respect to the decisions that have been made during the risk assessment process.

Therefore, the next step is to invite operators and engineers in trying out the hand-guided assembly workstation. The working hypothesis in inviting operators and engineers is that, personnel whose main responsibility during their working time in an assembly plant is to find the optimal balance between various production related parameters (such as maintenance time, productivity, safety, working environment, etc.) might have deeper insight into the challenges of introducing large industrial robots in the assembly line.

Acknowledgements

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