Safe Assembly Cell Layout through risk assessment – An Application with Hand Guided Industrial Robot

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Abstract

Risk assessment is a systematic and iterative process which involves risk analysis where the probable hazards are identified and 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 being 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 cell which takes into account the safety and productivity concerns of automotive assembly plants.

1. Introduction

Recent advances in industrial robot design, control systems as well as sensor technologies have made it possible for industrial robots to be used safely within final assembly lines [1,2]. Such an application of industrial robots are referred to as collaborative assembly and are expected to enable manufacturing flexibility[3,4] as well as improve the ergonomic work environment [5] of operators. The functional principle of collaborative assembly is to combine the characteristics of industrial robots with the superior cognitive and decision making skills of the operator with the aim of efficiently completing assembly tasks.

Large industrial robots can carry higher payload and have longer reach than robots specifically designed for collaborative work such as UR10 [6] or Kuka Iiwa [7]. These physical characteristics coupled with the possibility to work without physical barriers broadens the possibility of application of these robots. However, such robots pose serious risk resulting in injury [8-10]. To ensure a safe work environment, International safety standards [11-13] suggest that a detailed risk assessment be carried out to mitigate risks through inherent safe design or through risk reduction measures.

Risk Assessment is a structured and detailed process of identifying hazard, estimating the risk and recommending effective solutions to mitigate the risks. This article aims to detail the final design of a collaborative assembly cell which is the outcome of an extensive risk assessment process. The risk assessment is focused on an assembly cell where the task is the installation of a flywheel housing cover on a heavy vehicle engine.

This article is structured as follows. In section 4, an overall description of the methodology used to conduct the research will be presented along with limitations for the analysis and will be based on a theoretical description elaborated in section 2. A brief description of a manual assembly station will be made in section 3 and a detailed description of the layout of the collaborative assembly station in section 5. The design choices will be further discussed in section 6 and will conclude by highlighting the role of standards in the overall design of the layout.

2. Theoretical Background

Cognitive skill such as hand-eye coordination has been cited as the main reason for the low level of automation within automotive assembly lines. Within the context of an assembly station, a robotic cell can includes one or more
robots and associated machinery designed with the purpose of completing assembly tasks [12]. When the nature of the task is unergonomic and repetitive, an operator can benefit with an industrial robot to help with carrying out such tasks, and such an assembly station is called a collaborative assembly station. In this respect, a collaborative assembly cell (fig. 1) is a predefined workspace for participants (operators, robots, other integrated machinery) to complete tasks [14].

![Fig. 1: Elements of a collaborative robotic workstation.](image)

2.1. Risk Assessment & Risk Reduction

Introduction of a robot into a manual assembly cell brings forth additional hazards whose potential to cause harm needs to be eliminated or minimized [11,12,15]. The machinery safety standard [15] suggest the practice of conducting risk assessment coupled with risk reduction measures to ensure the safety of the operator. Risk assessment is an iterative process of risk analysis following by risk evaluation. The risk analysis process consists of determining the limits of the machinery, identifying hazards along with an estimation of risk associated with the hazards.

The risk evaluation process aims to determine if a risk reduction is required and if so, propose safety-rated solutions as measures to eliminate or mitigate the risks. To effectively manage risks, the designer has the choice of implementing safe solutions through three steps: 1. Inherently safe design measures 2. Safeguarding and/or complementary protective measures 3. Information for use.

The risk assessment process is an iterative process that concludes when all probable hazards have been identified along solutions to mitigate the effects of these hazards have been implemented. There exists standardized practises to document the process such as [16], which also proposes that risk assessors, designers and users (operators, maintenance, line managers) with various expertise in the risk assessment process.

2.2. Robot and robotic system safety

Robot safety standards recognises the implementation of one or more of the following four different modes of collaborative operation 1. Safety rated monitored stop. 2. Hand Guiding 3. Speed and separation monitoring 4. Power and force limiting

These modes are in addition to the automatic mode, where the robot is moving along a preprogrammed path within a predefined robot workspace. Within the collaborative workspace – where the operator and the robot can collaborate to complete tasks – needs to be monitored as there is a high risk for hazards. To assist in the risk assessment, the standards specifies the performance requirements for the robot as well as the equipment such as safety-rated stop and contact force limitation [11–13].

2.3. Sensitive protective Equipment (SPE)

For industrial applications, the selection, positioning, configuration and commissioning of sensitive protective equipment (SPE) has been detailed in [17], and aims to define the performance requirements for these equipment. 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 mainly for the detection of the presence of human beings and can be used as part of the safety-related system [17,18].

The IEC 62046 also states the performance requirements for the SPE in terms of performance level (PL) with a rating ranging a to e. The SPE such as a laser scanner will correspond to a specific performance level and therefore, the selection of the equipment depends on the application. SPE are designed to monitor a predefined space and needs to be triggered for the hazardous machine to be shut down or stopped. Therefore, the positioning and installation dictates a minimum distance that needs to maintained from the hazardous zone. The reasoning being the safety system takes time to activate (also referred to as response time) and take necessary evasive procedure.

As noted by [18], when the safety system is triggered, these sensor use electrical safety signals and include laser curtains (fig. 2 (right)), laser scanners (fig. 2 (left)) and vision based safety systems such as the SafetyEye [19]. Compared to a physical fence, where the positioning and installation dictates a minimum distance that needs to maintained from the hazardous zone. The reasoning being the safety system takes time to activate (also referred to as response time) and take necessary evasive procedure.

As noted by [18], when the sensor is triggered, these sensor use electrical safety signals and include laser curtains (fig. 2 (right)), laser scanners (fig. 2 (left)) and vision based safety systems such as the SafetyEye [19]. Compared to a physical fence, where the operators and the machinery are physically separated, ESPE relies on the human being to occupy a predefined zone for the sensor to be triggered.

Pressure-Sensitive Protective Equipment (PSPE) have been standardized in part 1 to 3 of ISO13856 [22–24], 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 & floors. 2. ISO 13856-2 – Pressure sensitive bars, edges. 3. ISO 13856-3 – Bumpers, plates, wires and similar devices

2.4. Feedback Interfaces for Human-Robot Collaboration

As noted by Sarter [25], in complex human-automation collaborative systems, effective feedback between human and the automation device is critical to avoid hazardous situations. Feedback interfaces can provide the following function: 1. The operator has situational awareness of the state of the machine [26], 2. It allows the operators who assumes supervisory control to be aware of the change of mode i.e., the operator is able to effectively judge whether the robot is in automatic mode or in collaborative mode. Manufacturing plants employ warning lamps, buttons, floor marking etc., to provides situational awareness and control to the operator [27,28] and their use are advocated by the standards as the third step in risk reduction.

3. Case Study – 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 (weighs approx 20kg.) from the material rack and securing it on the engine block with fasteners. Currently, this is a manual operation (See Fig 3 (a)) and can be described as follows: 1. The operator picks up the FWC with the aid of a lifting device from position P1. 2. The operator moves from Position P1 to P2, 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), where it is aligned with the housing and then fastened with bolts with the help of pneumatically-powered devices. The alignment is aided by using two locating pins which are pre-installed on the engine block.

The figure 3 (b), 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) and after the secondary operation is completed, move the FWC to position 3 (P3). Position P3 is the hand over positions where the robot will come to a stop and signal the operator that the collaborative mode is activated. The operator can then hand-guide the FWC to Position 4 (P4). The robot is in collaborative mode from P3 – P4 – P3, where the operator hand-guides the robot and from P3 – P1 – P2 – P3, the robot is in automatic mode.

4. Methodology

A manual workstation where the task is the assembly of flywheel cover has been used as the platform to understand the benefits and challenges of implementing industrial robots in a collaborative environment. An overview of the method is depicted in Figure 4, where an assembly station from a heavy vehicle industry is used as a case study [29] with the objective of increasing the automation level [26] of the currently manual workstation (see Section: 3). The case study represents an assembly station which is manual-labour intensive and the working environment can be characterized as unergonomic [5].

These two reasons have been used to motivate the implementation of collaborative robots where the unergonomic tasks (lifting the heavy flywheel cover) are allocated to the robot and the cognitively demanding task such as the positioning of the flywheel cover has been tasked to the operator with aid of a hand-guiding device [14]. The introduction of a collaborative robotic solution implies serious safety issues to humans working in the vicinity. To manage these safety issues, robotic safety standards suggests that a detailed risk assessment process to be conducted followed by a risk reduction process with the objective of eliminating hazards and to mitigate risks by the implementation of protective measures [11,12,15]. The risk assessment was driven by industrial-safety needs and was aided by experts both from the industry and research institution. The first step for the risk assessment team is to identify hazards and conduct an analysis of the severity of injury. If is deemed necessary to reduce the effect of these hazards, the three step risk reduction process needs to be completed for each identified hazard.

4.1. Inherently safe design measures

The layout of the work-cell is critical to mitigate the risk of hazards and the first step is to establish the overall layout of the cell where all required machinery are to be installed. The machinery include the robot, part/material rack as well as additional integrated machinery. The physical limits will allow the engineer to suggest 1. the operator task 2. the robot task in automatic mode 3. the collaborative task – hand guiding the
flywheel housing cover

The layout can be used to limit the reach of the robot beyond the robotic workspace using both mechanical and software based solutions. Depending on the robot manufacturer one or more axis can be limited using mechanical stops and this will ensure that even under manual mode, the robot reach is limited. Through software, it is also possible to specify the robot workspace which must include the collaborative workspace. When deciding on the layout, access for operational activities such as material/part intake and exit, collaborative operation etc., needs to be considered. Additional risks are introduced due to these operational requirements and the effects of these hazards needs to be mitigated.

4.2. Safeguarding

Risks that cannot be eliminated through design can be mitigated through process design facilitated through the use of physical fences and safety-rated sensors. Hazards identified during the risk analysis phase needs to be taken into account operators entering the hazard zone accidentally or purposefully. Therefore, to avoid these hazards physical fences can be used at locations to constrain operator movement. At the location where operators needs to enter the collaborative workspace, these zones needs to be safeguarding with safety-rated devices such as laser curtains and safety mats. The performance of the equipment for the sensor systems as well as the robot are found in the data sheet.

4.3. Operational Use

Safety sensors provide the ability to ensure that the operators are safe by stopping the machine or removing the hazard. These situation – where operators trigger (accidentally or purposefully) the safety system – occur when they are not aware of the state of the machine. Therefore, design of the layout needs to consider the situational awareness of the operator and change of mode of the robot during risk assessment. Tools to complement situational awareness are warning lamps, floor markings, timer etc. and can also be used to convey mode change of the robot. In addition, buttons and enabling devices can be used to trigger mode-change of the robot.

These steps are referred to as risk assessment (hazard identification, risk evaluation and risk reduction) is an iterative process which involve various participants to actively contribute to the overall objective of arriving at a safe and productive work environment. In this respect, the risk assessor main task is the documentation and planning of the risk assessment activity.

4.4. Limitation

The starting point of the analysis is a layout that requires humans and an industrial robot to share a common workspace. An assembly workstation requires analyses of various requirements such as productivity (e.g.: task sequence and allocation, ergonomics), coordination with upstream and downstream work-cells, workforce and material planning etc., which will not be taken into account in this article.

There are several sources of hazards that will not be considered in this article such as hazards associated with the normal functioning of various machinery, environmental factors, electrical hazards etc., The discussion will be limited to mitigating risks associated with collaboration between the operators and the robot. As mentioned before, this article aims to describe an industry viable solutions and therefore uses guidelines from several regulatory standards. However, there are several standards related to physical fences, safety protective equipment (see section 2) etc., that are described and specified in its own standards and are often ordered as off-the-shelf products.

5. Result

The results presented are the outcome of a thorough risk assessment that was done to ensure a safe work process. In the following subsections, beginning with a description of the physical layout of the collaborative assembly cell, the operational procedure will be detailed.

5.1. The design layout of the collaborative assembly cell

The final design of the layout is shown in Figure 5. The layout of the work-cell is critical to mitigate the risk of hazards as mentioned in the robot safety standards and includes all required machinery. Physical fences are used to constrain operator movement and are designed to eliminate the risk of operator entering a hazardous zone. As the reach of the robot is 2700mm, the maximum height as required by standards were chosen (2200mm). The hand over position is critical to the design as this area needs to be monitored at all times. The entry to the hand over position spans a width of 2m and is monitored by laser curtains.

$$S = 1600 \times (t_1 + t_2) + 850$$

(1)

The Laser curtains (LS) is placed at the opening and is placed as shown in fig: 5. The monitoring height is the same as the height of the fences (2200mm). Equation 1 from the manufactures data sheet is used to calculate the distance 5 (850 mm), which is the minimum distance that LS needs to be installed from the hazard zone. $t_1 = 0.0085$sec is the response time for the
laser curtain obtained from the data sheet (Safety Light Curtain EOS4 [21]) and \( t_2 = 0.422 \text{sec} \) is response time for the robotic system (Robot stopping time estimated for 33\% extension and 35\% speed obtained for KUKA-KR210 [7]) to stop. The robot will be programmed to move at a maximum of 33\% of rated speed between P1 and P2 and 10\% when moving from P2 to P3. This is to ensure that there is sufficient distance between the operator and the hazard.

During the collaborative operation, as the laser curtains are inactive and will be activated by the operator after assembly of FWC. During this hand-guiding operation, the operator is focussed on the assembly task and may not notice an unauthorized person entering the collaborative or robot workspace. This is a serious risk and one way to mitigate this risk is to install pressure sensitive mats. This additional resource through visual signals (warning lights) can warn the operator of an intrusion and can take appropriate action. The selection and design of safety mats are dependent on the application. In this case, the safety mat should be sensitive to the weight of a human being (35kg [16]) and needs to cover an appropriate area. In addition to lamps that convey to the operator of the state of the machine, the collaborative zone is floor marked to show the boundaries. The robot is programmed to limit its motion only within this area during collaborative mode. However, the operator is in control of the robot (6 degrees of motion) within this area and is able to move the FWC with the aid of a hand-guiding tool with minimal effort (see Gopinath et al. [14])

5.2. Operational procedure of the collaborative assembly cell

We have discussed the use of ESPE and PSPE devices along with physical methods to reduce the risk of foreseeable hazards. As discussed in Section 2, through visual or physical techniques, the interface between the operator and robot can play an important role in ensuring safety by providing situational awareness to the operator.

To elaborate, after position P2, the robot moves to position P3 which is the hand-over position. Once the robot reaches this position, the Laser curtains are deactivated and signals to the operator that the robot is ready to be hand guided. This signal can be in form of warning light that turn from Red to Green (See Table 1) and the operating procedure would be for the operator to approach the hand-over position and take control of the robot with the aid of the hand-guiding tool. Once the operator presses the enabling device, the signal changes from Green to yellow to convey that the robot is in hand-guiding mode. This signal turn back to green and the robot stops its motion if the operator releases the enabling switch. The operator completes the task at position P4 and returns to the hand-over position. Then the operator engages a button on the hand-guiding tool to convey that the assembly task is complete. Then the operator moves out of the collaborative zone and presses a button outside of the workstation which initiates the automatic mode of the robot. The robot controller check if the robot workspace is free of any intrusion and starts the next work cycle.

6. Discussion

The final concept for the collaborative workstation designed to facilitate the assembly of a flywheel housing cover is shown in figure 5 and the details of the design have been described in section 5. Risk assessment is the method that have been employed to document the requirements and solutions in terms of safety and productivity. Safety of Machinery [15] points at various hazards that must be considered during the first step in this process (hazard identification) and in this article the focus has been to mitigate the effects of hazards associated during collaboration. The analysis and evaluation of the hazards are subjective in nature. For example, the severity of injury are quantified in terms of minor, moderate and serious. Therefore, expert knowledge is required where all users who have an interest in the proper functioning of the station be involved during the risk assessment.

During the risk reduction process, solutions to mitigate the risks are proposed and evaluated in a order from inherently safe design to information for use. Several solutions can exist depending on the hazard and the preferred sequence to carry out the assembly task. Therefore, the final design might reflect a pragmatic solution which takes into account many relevant factors such as task planning, safety and productivity.

Situation awareness and mode-error have been highlighted in section 2 along with techniques to address these issues. It is easy to propose solutions such as warning lamps and enabling devices, but from the point of the operators, it is important that these interfaces do not interfere with their task and that the operator feel in control of their work environment. The guiding principle for handling these issues during the risk assessment process has been to minimize the number of interfaces. If the system becomes complicated with several feedback interfaces, the productivity of the station might decrease resulting from

<table>
<thead>
<tr>
<th>Pos.</th>
<th>Interface</th>
<th>ESPE</th>
<th>PSPE</th>
<th>Mode</th>
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<td>Active</td>
<td>Active</td>
<td>Auto</td>
</tr>
<tr>
<td>P2-P3</td>
<td>Red-Green</td>
<td>Active</td>
<td>Active</td>
<td>Auto</td>
</tr>
<tr>
<td>P3-P4</td>
<td>Green-Yellow</td>
<td>Inactive</td>
<td>Active</td>
<td>Collab.</td>
</tr>
<tr>
<td>P4-P3</td>
<td>Yellow-Green</td>
<td>Inactive</td>
<td>Active</td>
<td>Collab.</td>
</tr>
<tr>
<td>P3-P1</td>
<td>Green-Red</td>
<td>Active</td>
<td>Active</td>
<td>Auto</td>
</tr>
</tbody>
</table>

Table 1: Overview of the robotic system detailing Operating modes

Fig. 5: Top view of the Hybrid-Assembly cell. The layout shows the operating workspaces as the modes for operation of the robot along with the sensors integrated into the system to enable a safe collaborative workspace.
increased cognitive load for the operator. Another important
design decision is the location of these interface elements.
Warning lamps needs to be easily visible while buttons (e.g.
to activate change of mode) should be designed so as to avoid
misuse or accidental activation.

The result of the risk assessment have led to the layout
design of a collaborative assembly station where a large
industrial robot collaborate with operators. In effect,
the robot has been used as a flexible lifting device that allow
the operator to accurately position the flywheel housing
cover on the engine block. Compared to the lifting tool which is
currently in use today, the hand guiding operation does not exert
a reactionary force on the operator. This ergonomic problem has
been minimized to a large extent. He additional advantage of
using a robot is its ability to be programmed to function in
automatic mode. This is the traditional use of industrial robot,
which can provide significant benefit in terms of productivity
and reduced reliance on manual labour.

7. Conclusion

This article detail the outcome of the risk assessment which is
the design of the layout of the collaborative assembly cell. This
layout can allow large industrial robots to be used in
a collaborative manner. The risk assessment process uses
guidelines from various standards including the machinery and
robotic safety standards which has allowed the risk assessors to
focus on pragmatic solutions for ensuring safety on an assembly
line. The final layout uses two modes of collaboration, which are
hand-guided & Safety rated monitored stop complemented
by feedback Interfaces such as warning lamps. It was also
highlighted that mode change (e.g. change from automatic
to collaborative mode) errors can be better managed through
these feedback interfaces. In conclusion, standard compliant
measures can allow a traditional industrial robot to be used as
a flexible and programmable lifting device, that provide
significant benefits to the ergonomic work environment of the
operator.

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