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Risk Assessment Process for Collaborative Assembly – A Job Safety Analysis Approach

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Abstract

International safety standards state that risk assessment is the first step in understanding and eliminating hazardous work environment. The traditional method of risk assessment using Job Safety Analysis, where sequential tasks of the operator are analysed for potential risks, needs to be adapted to applications where humans and robots collaborate to complete assembly tasks. This article proposes a novel approach by placing equal emphasis on various participants working within their workspaces. An industrial case study wil be used to showcase the merits of the process when used at an early stage in the development of a collaborative assembly cell.

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1. Introduction

A safe collaborative assembly cell, where operators and industrial robots collaborate to complete assembly tasks is seen as an important technological solution [1,2] for several reasons including: 1. The ability to adapt to market fluctuations. [3]. 2. Improve productivity and 3. Improve ergonomic work environment [4].

Operator safety is an important source of concern for collaborative assembly as impact with a moving robot can cause serious injury. According to the International safety standard, risk assessment is the first step in understanding and eliminating hazardous work environment [5,6]. For non-collaborative robotic cells, risk assessment were carried out with the understanding that robots and operators do not interact. That is, a robots can only be operated in the automatic mode within a designated workspace and intrusion should result in a monitored stop of the robot. Physical barriers such as safety fences were used to ensure operator safety by avoiding the possibility for collision.

In practice, collaborative robotic assembly system seeks to remove these barriers to enable closer interactions between operators and robots, Therefore, risk assessment should consider both operators and robots as valid participants to ensure safety of operators and productivity of the assembly station. With a focus on operator safety, international safety standards defines the use of collaborative task only within a predefined work area called the collaborative workspace [6].

To ensure safety and enable task sharing, safety standards require that the assembly cell is continuously monitored during execution of the task. Therefore, the motion of the robot and the operator within the assembly cell must be monitored using safety sensors [7]. such as vision system, safety mats, proximity sensors, etc.

Before safety devices are selected and installed, a systematic risk assessment will ensure that appropriate devices and procedures are implemented [8]. Additionally, risk assessment can also be used to ensure compliance with various regulatory bodies.

This article presents a work process for risk assessment that emphasizes on the interactions between the operator, robot and the work environment (See Fig:1). As collisions are a major cause of injury and damage [8–10] the article explores the methodology of Job Safety Analysis to dissect an assembly task into subtasks and critically analyse subtasks for hazards and suggest solutions for perceived risks.

This article is structured as follows. Section 2 examines the state of the art that focusses on risk assessment methodologies of robotic systems and will also detail some of the relevant robotic and machinery safety standards. Section 3 provides a generic overview of a collaborative assembly cell in terms of the participants involved, their tasks within the assembly cell and the workspace allocated to complete the tasks. Section 2 and 3 forms the basis for the proposed risk assessment process

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which will be described in section 4. Section 5 will briefly detail an industrial case study where the task is to assemble a flywheel housing cover. Also, a detailed description of the application of the assessment process (section 5.1) will show how the design and safety requirements were acquired through this process which resulted in a tool for safely hand-guiding an industrial robot.

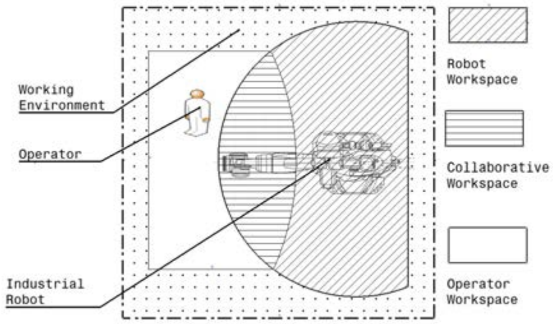

Fig. 1: Illustration of the interaction between the three participants of a collaborative assembly cell within their corresponding workspaces.

2. State Of The Art

Academic literature describes various methods to conduct risk analysis for robotic systems which can be broadly described as quantitative and qualitative. Dhillon & Fashandi [9] and Etherton [8,10] has outlined a few of the commonly used risk analysis methods for robotic systems though Dhillon & Fashandi focuses on Fault-Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) as relevant methods in their article. Etherton refers to Job Safety Analysis for conducting risk assessment in application areas where operator tasks have to be considered.

The quantitative Fault-Tree Analysis require probabilistic information about occurrence of failure, which can then be used to calculate a combination of fault-events that could lead to a robot related accident. The qualitative Failure Mode and Effect analysis is used to understand and document all possible failures (and its effects) so that corrective actions can be suggested to mitigate the sources of failure. FMEA uses a tabular form to document each failure mode and its effect along with the probability of failure and possible solution.

Compared to Job Safety Analysis (JSA), FMEA and FTA are higher fidelity analysis methods as the basic requirement for their usage is that information of possible risk must be known beforehand. Therefore, for the development of new collaborative assembly cells, these methods are not immediately applicable, though they are widely used when information of the risks are known or can be better estimated. In addition, these methods do not consider task that has to be performed and therefore Job Safety Analysis [8,10] is a better choice to conduct risk assessment. Job Safety Analysis aims to break down an assembly task into subtasks. The procedure is to analyse the subtasks for hazards and suggest methods or procedure to reduce or nullify the effects of these hazards.

Industrial machinery and their use within a manufacturing plant are required to adhere to safety standards. Collaborative assembly brings forth additional risks that arise when operators and robots have to work together. Risk assessment methodologies should allow for the possibility of arriving at solutions that meets the requirement of safety standards, some of which are:

1. General machinery such as end effectors, external actuation, power delivery are expected to follow the Machinery standard – *SS-ISO 12100:2010 – Safety of Machinery – General principles of Design – Risk assessment and risk reduction (ISO 12100:2010)* [5]. The standard defines and lists out the requirements and procedure to conduct risk assessment.

2. Industrial robot safety design are governed by part one of *SS-ISO 10218-1:2011 – Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots*[6]. This standard focusses on safety requirements of manipulators and therefore is targeted at robot manufacturers whereas part two of *Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration* is focussed on robotic system integrators [11] .

3. The newly released ISO/TS 15066 *Robots and robotic devices – Collaborative robots* [12] specifies requirements for collaborative industrial robot systems and the work environment. This Technical specification is intended to act as supplement to the Industrial robot safety standards.

3. Collaborative Assembly Cell

In this section, a collaborative assembly cell will be characterized in terms of the tasks that will be performed, the participants that are responsible for the tasks and the workspace to complete the task. The main purpose of describing an assembly cell in terms of tasks and participants is to map the interactions between them (See Figure: 1).

3.1. Workspace in a Collaborative Cell

International safety standards suggest the following workspaces for a collaborative assembly cell [6,13]:

1. **Robot Workspace:** Within the robot workspace, an industrial robot can be programmed to move in automatic mode at rated speed and must stop if the there is an intrusion. Traditionally, the robot workspace is closed off from external interaction using physical fences or safeguards [6].

2. **Operator Workspace:** The area assigned to the operator to do his task can be termed as operator workspace and can be monitored for safety with corresponding reduction of speed if the operator goes near the robot and complete stop if the operator is close to the robot to warrant a complete stop.

3. **Collaborative Workspace:** The collaborative workspace allows the robot and the operator to work together, which means that the robot and operator share a common workspace. The nature of assembly task is described in

Section: 3.2. Though the robot can be moved in automatic mode within the collaborative workspace, the speed of the robot is limited [12]. Also, there must be Human-machine interfaces (HMI) to signal to the operator that the robot can be tasked in collaborative mode.

3.2. Assembly Task in a Collaborative Assembly Cell

Collaborative assembly refers to the possibility of completing assembly tasks by an operator and a robot together. The nature of these tasks were summarized by Krüger et al. [3] in terms of task allocation in the assembly process as well as in terms of time that is shared to complete the task. In other words, Krüger's demarcation refers to the degree of collaborative work. The safety standards [6,11] suggest the following application areas for collaborative robots which can include one or more of the following: 1. Safety-rated monitored stop. 2. Hand guiding. 3. Speed and separation monitoring and 4. Power and force limiting by design or control.

3.3. Participants in a Collaborative Assembly Cell

In a collaborative assembly cell, there are three distinct participants.

1. **Industrial robotic System:** Industrial robotic system as recognized by the safety standards include the manipulator, end-effector and external sensor system that are designed to work cohesively. These separate parts must conform to the corresponding safety requirements and must be designed to work safely with operators during the collaborative mode.
2. **Operator:** An operator is the trained personnel expected to share the robotic cell but can also include other personnel present in the vicinity. They are also expected to be take responsibility of an assembly cell and shut down the assembly system in case of emergency.
3. **Working environment:** The working environment should also meet the standards for robotic safety as external interferences can lead to injury or production delay. The working environment includes equipment located near to the assembly cell that can interfere with the intended functionality of the robotic cell.

4. Job Safety Analysis for Collaborative Assembly Cell

Risk analysis can be used to drive the design of the robotic system that is safe for the operator and ensure a productive assembly cell. Therefore, it has to be understood as an iterative process which begins when the basic functionality [14] of the assembly cell is established i.e., cell layout to carry out the assembly task is defined. The proposed work process that emphasis the interactions between the participants and their tasks can be described as follows:

Step 1: The assembly function of the production cell can be reformulated into discrete and sequential subtasks. The subtasks are allocated to the participants who will perform them within an allocated workspace. That is, the first step is to divide the assembly task into subtasks and establish participants and workspaces for each subtasks.

Step 2: Job Safety Analysis require that the subtasks are critically analysed for hazards. In the second step, the objective is to analyse the subtasks allocated to each of the participant. To estimate all possible hazards, each subtask associated with a participant can be critically analysed by focusing the analysis on the interaction of the participant with the other set of participants. For example, if T1 is a subtask to be performed by an operator, the analysis should capture the interaction of T1 has on the robot as well as the Working Environment.

Step 3: In the final step, the causal factor for each of the hazard can be documented along with the effect of the risk. Information on the causal risk along with the effects can be used to suggest solutions to mitigate the risks. Probable solutions can be in form of assembly cell monitoring solutions, safety by design, guidelines from safety standards etc., which can then be used to specify design requirements for the robotic system.

5. Case Study: Hand-guided assembly of heavy parts

The assembly task is to install a flywheel housing cover on the flywheel housing. Currently, the operator has to secure the flywheel housing cover on a lifting device and then manually push it to the correct location where two pins are used to guide the cover onto the housing. Then the assembly are fastened using bolts that are tightened by the operator using a hand-held device.

In the proposed collaborative assembly cell, the robot is a lifting device that can be programmed to select the correct housing cover and present it to the operator. The responsibility of the operator is therefore reduced to precisely locating the cover onto the flywheel housing. The robot can be programmed to push the housing cover with a predefined force thereby reducing the assembly task to installing and tightening the bolts.

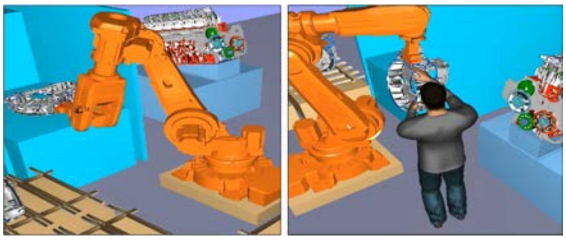

Fig. 2: Illustration of a conceptual model of a collaborative assembly cell. The operator is responsible for guiding the robot to the correct location. The robot is used as a flexible lifting device [4].

5.1. Risk Assessment of a Collaborative Cell

To elaborate the process of risk assessment presented in Section:4, the case study described above will be used to illustrate the basic idea of the proposed work process.

The first step is to divide the task of installing the flywheel housing cover into discrete subtasks which are allocated to the participants. The subtasks are: 1. Robot moves from home position to programmed point to pick up the flywheel housing cover (RT). 2. Robot activates the end-effector to clamp the cover (RT). 3. Robot moves to take over point in the collaborative workspace (RT). 4. Operator moves towards the robot in the collaborative workspace (OT). 5. Operator will move the robot (Hand Guiding) towards the assembly point (CT). 6. Operator will position the cover on the fly wheel housing (CT). 7. Operator will activate the release of the flywheel housing cover from the end effector (CT). 8. Operator engages the robot to move to the home position (RT). 9. Operator will fasten bolts (OT).

RT, OT and CT correspond to the robot, operator and collaborative tasks respectively. In the next step of the risk assessment process, each subtask needs to be critically analysed to eliminate hazard and in the final step the causal factors and possible solution to mitigate the risks needs to be documented. To illustrate how the risk assessment process have been used to develop safety and design requirements for the assembly cell, consider Task 4 where there is a possibility of collision of robot and operator. A possible solution is to develop monitoring systems that can stop the robot if an intrusion is detected. To mitigate the risk of production delays a visual indicator can be used to warn the operator that the robot is not in collaborative mode and it is not okay to enter the working zone.

The green visual indicator shown in Fig:3 (Left) communicates to the operator that the robot is ready for collaboration and disables the monitoring system. During hand-guiding of the robot (Task 5), it is important that the operator is safe while undertaking the task. There is a possibility for injury to the operator's hand during robot motion. A solution is to ensure that both the hands are engaged to move the robot. Fig:3 is a two handed guiding tool with two three-position enabling device ergonomically placed behind the handle that ensures both hands are used to move the robot. Annex C of Safety Standard ISO 10218-1 [6] details the functional and safety requirement of the three-position enabling device while Annex D of Safety Standard ISO 10218-2 [11] details the truth values when two enabling devices have to be used together. Additionally, an emergency stop button (The large red button) have also been implemented as suggested in the safety standard (Section 5.5.3.3. of ISO/TS 15066:2016 [12])

Fig. 3: A concept for a hand-guiding device that can used to move the flywheel housing cover (left) into position. A switch that increases the accuracy of robot motion to enable precise assembly (Right Top). The yellow indicator light conveys to the operator that the guiding pins are engaged and that the cover can be released. (Right Bottom).

In order to maintain good quality by ensuring accurate installation of the flywheel housing cover (Task 6), the risk assessment suggested an additional button (Fig:3 Right Top) to enable precise movement of the robot. This has the possibility to maintain production quality as it was noticed that, though hand-guiding improve assembly flexibility, it is difficult to accurately position the locating pins over the mating holes. For the majority of hand guiding motion, precise movement is not required and is only required once the pins are close enough and then the operator needs to engage precision movement to accurately locate the pins into the mating holes.

The light indicator shown in Fig:3 (Right Bottom) were incorporated to communicate to the operator that Task 7 can be executed i.e., it indicates that the both the pins are secured and it is safe to release the flywheel cover from the end effector. Safe design of the end effector will be dictated by safety of machinery standards [5] along with other relevant standards that govern electrical systems, ergonomic standards etc.

6. Conclusion

The overall goal of undertaking a risk assessment is to document all possible hazards and suggest methods to curtail them. Hazards arise from various sources such as malfunction of equipment, unexpected collision etc. It is possible to avoid them through safety-focused design and establishing work procedure that circumvent probable risks.

It is not impossible to accidentally fail to foresee a hazard, as a collaborative assembly cell represents a complex interactions between operators and machines. A structured approach to estimating risk is required that will allow the risk assessor to foresee potential hazards. To aid in this effort of identifying hazards, an assembly cell has been characterized as *workspaces* for *participants* to complete *tasks*. As shown in the article, such a characterization places equal emphasis on the participants that allows for mapping of the interactions between them and their work environment, thereby facilitating a focused analysis of hazards and solutions to eliminate them. The assembly tasks for each participant were documented and analysed using Job Safety Analysis Method for risk mitigation.

Safety standards suggest that risk assessment is to be done in cooperation with the user. Within an assembly line, the users can be the operators, line managers or other experts who might be familiar with the technical risks and may or may not have the knowledge or experience to suggest proactive measures to avoid potential hazards. For example, a robotic system specialist will have the required knowledge to suggest design requirements for end effectors but may not have the required expertise to suggest layout of vision sensors that can be used for safe monitoring of the assembly cell. Therefore, the risk assessment process must facilitate inputs from experts as well as users.

It can be argued that collaborative robotic systems are more exposed, due to the absence of physical fences, which opens up more venue for accidents. Therefore, it becomes imperative to undertake design decisions with a focus on safety. It was shown that risk assessment when undertaken at an early stage of development, not only enables facilitation of safety requirements that meets regulatory safety standards but also requirements that ensures production quality.

To conclude, the risk assessment proposed in this article is aimed at an early stage of development of a collaborative assembly cell. The work process aims to act as a way to ensure that appropriate devices and procedures are implemented from the beginning so that knowledge can be gained about the robotic system. Then, it becomes possible to use higher fidelity analysis methods to assess risks resulting in the development of a safe and productive collaborative assembly station.

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