Supporting Safety Assessment in Human-Robot Collaboration using Process Models

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Abstract

Future manufacturing scenarios increasingly rely on human-robot collaboration, where safety is a critical concern. To ensure safe collaboration in industrial automation, the underlying assembly process must be adequately considered. Therefore, we present a framework that uses graphically annotated process models to visualize safety hazards in collaborative assembly processes, providing experts with an easy-to-understand tool for their analysis.

Keywords

Safety Assessment, Process Models, BPMN, Human-Robot Collaboration, Collaborative Robot

1. Introduction

Robotic systems play a vital role in flexibilizing manufacturing processes, with collaborative robots (cobots) increasingly being used to semi-automate production tasks. In these settings, humans and cobots share the same workspace, operate in vicinity, spatially overlap in their actions, and collaboratively work on the same task. Therefore, a significant challenge in human-robot collaboration (HRC) is ensuring safety.

Research has found model-based approaches to be a promising paradigm to foster early analyses and safety assessment of robotic systems (e.g., [1, 2]). However, for robotic systems used in production, particularly the production process needs to be considered for safety analysis, as this hugely influences overlaps and potential mishaps in the interaction between human and cobot. Therefore, as a first step, we propose using annotated process models to assess the safety of HRC.

In this paper, Business Process Modeling Notation (BPMN) is used to (a) specify the production process executed by cobots and humans, and (b) assess the safety of the HRC using graphical annotations embedded in the process model. BPMN models thereby help in capturing the timely dependencies between different process steps, which are crucial for safety assessment.

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2. Related Work

In recent years, the rise of cobots interacting with humans in shared environments has raised safety concerns about HRC systems. In software and systems engineering, model-based approaches aid in managing complex development. Daun et al. [2] demonstrated the use of goal models for early safety analyses of HRC systems. Awad et al. [3] focused on model-driven risk assessment to identify workplace hazards and estimate the impact of safety measures.

Safety modeling in manufacturing, especially under the Industry 4.0 paradigm, is crucial as failures can lead to significant harm [4]. Process models, particularly those based on the BPMN 2.0 standard, have been proposed to model collaborative behaviors and ensure safety in such interactions. Corradini et al. introduce an approach, which integrates formal verification techniques into BPMN collaboration models to ensure software quality and safety, demonstrating BPMN's applicability in safety-critical contexts [5]. Additionally, Corradini et al. propose collaboration diagrams based on BPMN to model multi-robot collaboration, and highlight the potential for extending these models to HRC [6].

The BPMN standard has also been integrated with other modeling techniques to enhance safety management. For example, Mohammedi et al. developed a framework combining iStar with BPMN to analyze trustworthiness and safety requirements in collaborative operations, emphasizing how BPMN can be used to model responses to safety constraint violations [7].

3. Using Process Models to support Safety Assessment in Human-Robot Collaboration

Safety analysis is a critical and complex step in planning HRC assembly sequences. This is particularly important as most hazards occur during process operation and maintenance [8]. To ensure human safety, the process must be systematically analyzed in detail to prevent overlooking any safety risks. The identification and severity of these risks significantly influence the selection of appropriate mitigation strategies and determine whether the process is suitable for close human-robot collaboration. Early identification of potential exclusion criteria in the planning process is therefore highly beneficial. The use of BPMN can address this gap by providing a detailed process analysis that captures these critical dimensions, thereby reducing the likelihood of overlooking relevant safety risks.

To improve safety analysis in HRC, the use of graphically annotated BPMN process models is proposed. We adapt the security-oriented extension of BPMNs by Salnitri et al. [9] for safety risks in the area of HRC. Specific safety risks are mapped to corresponding assembly steps within the BPMN model, providing a detailed and systematic approach to analyzing safety. This use of BPMN ensures that safety considerations are thoroughly integrated into the process design, allowing for better identification and mitigation of potential risks.

Table 1 shows graphical warning signs for eight common HRC safety risks that are used to annotate the BPMNs. In addition, a multiple risks sign is introduced to indicate safety risks in sub-processes of the BPMNs. Figure 1 shows the use of the BPMN process model to visually highlight safety risks directly related to the process steps they might be triggered in.

The example, shown in the figure, is taken from an assembly process for toy pickup trucks.

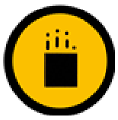
	**Collision with human operator:** Robot collides with the human operator, causes injuries to the human, potential damages to the robot and time loss.		**Repetitive strain injury:** Human gets injured due to a repetitive task executed over a longer time.
	**Crushing an object:** Robot crushes an object during assembly. This can lead to a damaged object or gripper.		**Human gets tired:** Human gets tired due to simple and repetitive tasks, leading to possible follow up errors.
	**Losing an object / Falling object:** Robot loses an object while manipulating it. A falling object can injure the operator, can get damaged or damage other objects.		**Improper tools use:** Human or robot uses a tool in a way that is not meant to, increasing the risk of damaging an object, the tool itself or injuring the operator.
	**Instable object placement:** Human or robot does not place an object properly. This can lead to falling or false assembly of the object.		**Multiple Risks:** The multiple risks symbol is used for sub-processes that contain more than one possible risk. By extending the sub-process the risks are shown in detail.
	**Communication breakdown:** The communication between human and robot is not working. This can lead to either the robot or human getting no signal to continue a process and therefore generating time losses.		

Table 1

Graphical warnings of common safety risks in HRC assembly with their respective descriptions (Symbols were generated using AI tool OpenAI-DALL-E 2).

The BPMN model provides a detailed representation of the collaborative assembly process. The cobot initiates the process by picking and placing the load carrier, cabin, chassis and front axle upside down in an assembly bracket. Meanwhile, the human operator prepares the axle holders by inserting two screws in each holder. The operator then fixes the front axle with the prepared axle holders with an electric screwdriver. This process is repeated for the back axle. The robot's five pick and place operations can be broken down further to assign risks to more specific actions; they are therefore shown as sub-processes. "Picks and places load carrier" shows an example of the subdivision of the processes into the actions of reaching, grasping, bringing and releasing, with the specific safety risks that can occur in each case.

The warning signs embedded in the BPMN allow safety risks to be directly associated with specific assembly steps and are easier for the user to understand than textual annotations [10]. Due to the depicted process flow, the presented BPMNs can also be used to highlight successive risks, which is particularly interesting when they influence each other. For example, in our toy truck use case, a possible communication breakdown is immediately followed by the risk of a collision between the operator and the robot. The lack of communication can significantly increase the likelihood of such a collision.

4. Conclusion

This paper examines a systematic safety analysis for industrial HRC by integrating safety risks into BPMN process models. Unlike other approaches that may only address specific aspects of HRC, our approach integrates safety analysis from the early stages of development. Our annotated BPMNs provide a structured notation that meticulously captures safety risks for each task and the entire sequence, providing an easy-to-use tool for safety professionals.

Our approach emphasizes using BPMN as a proactive tool for safety assessment. By visualizing the process flow in BPMN, not only potential safety risks for specific steps, but also successive risks become more apparent. This enables early identification and mitigation of risks in HRC, improving the overall safety and reliability of the production process from the outset.

In future work, we want to enhance the informative value of our annotation by emphasizing the severity of a risk or a series of risks by employing a color-coding system. Furthermore, we aim to determine if automated annotation is feasible for specific BPMN components, such as a communication error for the message symbol.

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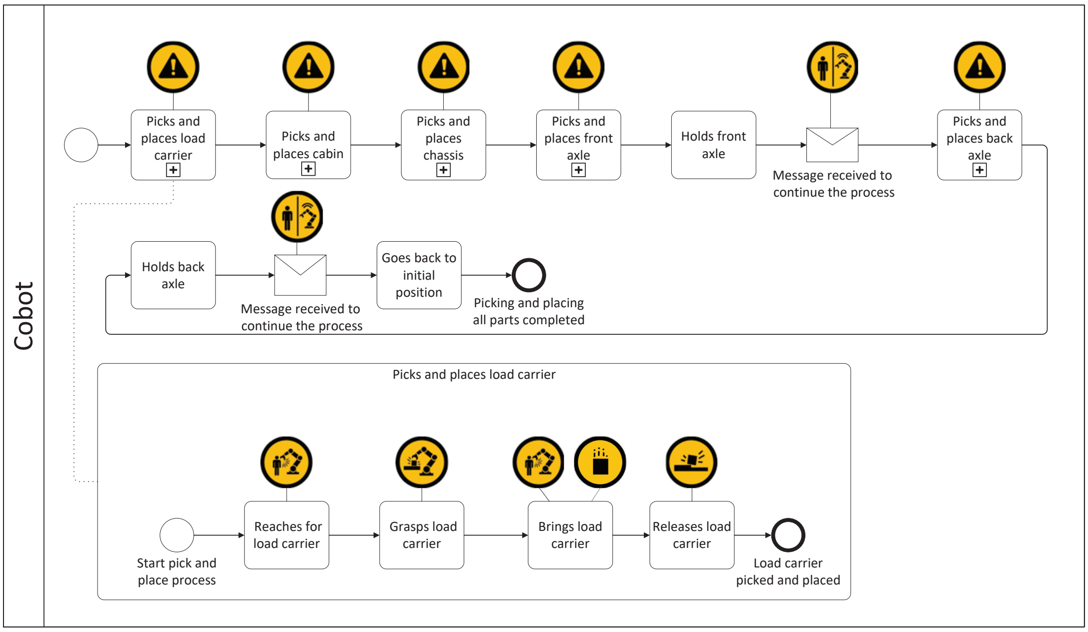

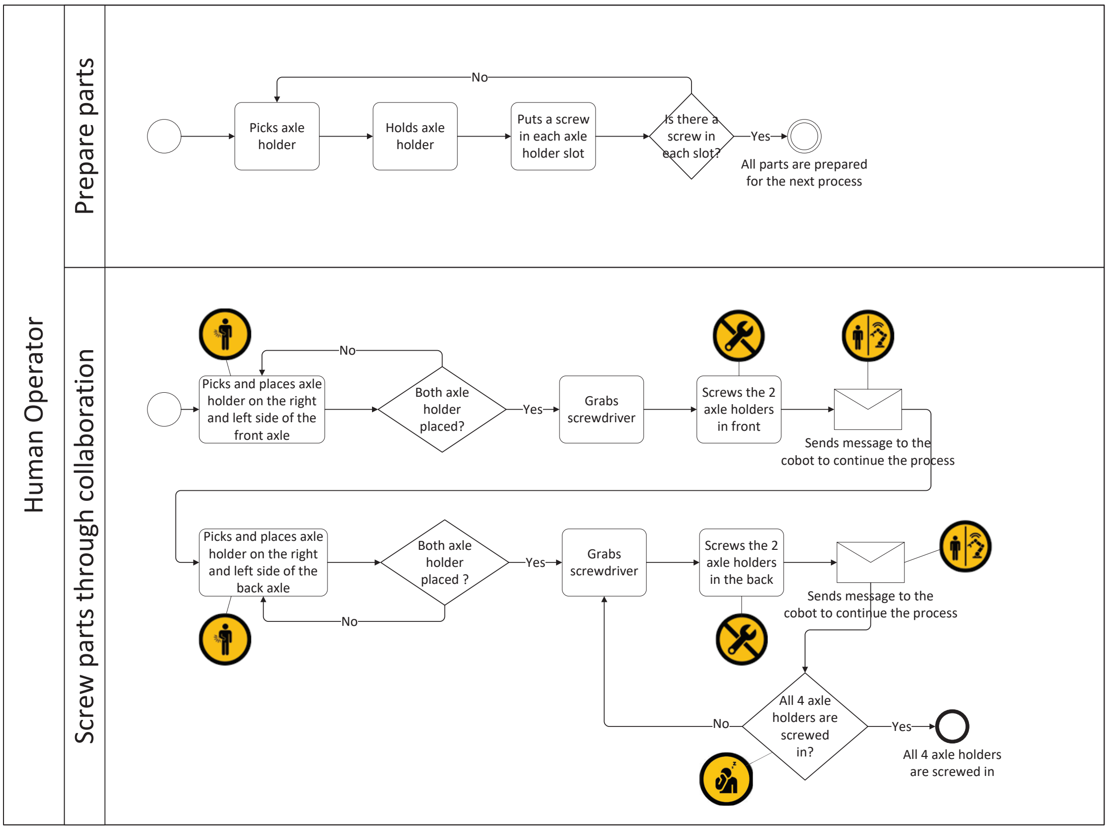

Figure 1: BPMN process model for the collaborative assembly of a toy pickup truck. The safety risks of the individual assembly steps are annotated with graphical warnings to provide the expert with a quick overview and to support the safety assessment (Symbols were generated using AI tool OpenAI-DALL-E 2).