28th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2018), June 11-14, 2018, Columbus, OH, USA

Demonstrators to support research in Industrial safety – A Methodology

Varun Gopinatha, Kerstin Johansen, Micael Derelöv

"Linköping University, Department of Management and Engineering, Division of Machine Design, Linköping, Sweden"

Abstract

Activities to support manufacturing research are carried out with the intention to gain knowledge of industrial problems and provide solutions that addresses these issues. In order for solution to be viable to the industry, research activities are carried out in close collaboration with participants from the industry, academia and research institutions. Interactive research approach motivates participants with multi-disciplinary perspective to collaborate and emphasizes joint learning in the change process. This article, presents a methodology, where participants with different expertise can collaborate to develop safety solutions. The concept of a demonstrator, which represents cumulative result of a series of research activities, is presented as a tool to showcase functioning and design intent in a collaborative research environment. The results of a pilot study, where manufacturing professionals evaluated design decisions that resulted in a demonstrator, will be presented.

© 2018 The Authors. Published by Elsevier B.V.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/)
Peer-review under responsibility of the scientific committee of the 28th Flexible Automation and Intelligent Manufacturing (FAIM2018) Conference.

Keywords: Collaborative robots; Industrial Safety; University-Industry Collaboration; Risk Assessment

1. Introduction

As manufacturing companies strive to deliver customized products, recent advances in key technologies (such as sensors & robotics) enables this objective through the development of flexible manufacturing solutions [3, 12]. To capitalize on the perceived benefits of these techniques, it is beneficial to understand the limitations as well; failure to do so might result in under-performing and costly investments. To aid in this effort, research takes the form of a collaborative endeavor between participants from the industry and research institutions and is referred to as University-Industry collaboration (UIC). This is seen as an approach to improve innovation by facilitating sharing and transfer of technology-related knowledge and experience [1].

* Corresponding author. Tel.: +46-013-28 2510
E-mail address: varun.gopinath@liu.se
Applied research methodologies (such as DSM [2]) allow the researchers to propose solutions to the underlying research questions. However, the researchers are faced with two challenges: 1. acceptance of solution [13] and 2. transfer of knowledge to decision makers [13]. Research activities within a UIC context allows researchers to emphasize on real case studies and to formulate research questions by observing the practices in the industry [19].

In this article, a methodology that was developed to allow participants with different disciplinary perspectives to collaborate and propose safety solutions will be detailed. To facilitate this collaboration, we propose the concept of a demonstrator as a tool to 1. guide the iterative design process that leads to a solution which is acceptable to the industry and 2. transfer research knowledge to decision makers. The methodology requires development of the demonstrators at various stages, which allows participants to interact and evaluate it from their perspective. In order to evaluate the notion of research supported by demonstrators, a pilot study with six personnel from the industry were invited to try out the hand-guided robotic assembly. They were later interviewed in order to document their experience and insights. In addition to the methodology, the results of the interview will also be presented.

The article is structured as follows: Section 2 briefly details literature, which forms the basis for the demonstrator-based-research methodology presented in section 3. A laboratory demonstrator describing a hand-guided collaborative operation with large industrial robots will be presented in section 4. In order to evaluate the demonstrator, engineers and operators were invited to test the demonstrator, and the results of the interview is detailed in section 5 (Appendix A lists the interview questions). Section 6 discusses the results – demonstrator based research methodology & interview – with concluding remarks in section 7.

1.1. Background

Collaborative operation is defined as a state in which a purposely-designed robot system and an operator work within a collaborative workspace [27]. Traditional industrial robots – robots that have long reach and large payload capacity – can be used in collaborative operations as their physical performance can be utilized to support operators in assembly tasks. Laboratory studies carried out by Karwowski et al. [10, 11] shows that operators who have had several years of experience were not able to judge the reach of the robot in a physical environment. Reviewing a fatal accident, Sanderson et al. [20] notes that there are several causal factors that needs to be considered when designing robot workstation. Therefore, researchers who are attempting to understand the requirements of safety needs to recognize the views of various stakeholders such as operators, maintenance engineers, line managers, etc.

The case study presented in section 4 was developed in collaboration with members from the automotive industry, academic and researcher institutions. An aim for the research project was to develop a laboratory demonstrator in order to showcase safety solutions for collaborative operations with large industrial robots [6, 7, 8, 9].

2. Theory

This section describes theoretical aspects of safety, standardized methodology to manage risks, followed by a brief background on approaches to collaborative research.

2.1. Industrial Safety – Risk Assessment (RA), Risk Reduction & Human factors

A hazard is defined as a potential source of harm [24] and according to Ericson [5], an accident is an event which occurs when a hazard is activated by an initiating mechanism. Leveson [15] states that hazards are designed into a system, and therefore, the potential of hazards to cause injury needs to be eliminated or minimized to an acceptable level. Safety issues associated with collaborative operations are multi-disciplinary and therefore, require expertise in domains [24] such as 1. Machine Safety and Safety Standards [24, 25, 26], 2. ergonomics [4] & 3. Human factors [18].

ISO 12100 [24], the machinery safety standard suggest the practice of conducting risk assessment followed by risk reduction to manage risks associated with machine operations. Task-based risk assessment [25, 26] develops the RA by including the sequence of operations that is to be performed in the robot workstation. RA is an iterative process of risk analysis followed by risk evaluation. Risk analysis is carried out with the aim of identifying hazards and estimating the effects of these hazards. When the risks are estimated, risk evaluation is carried out to determine
whether the effect of the hazard warrant a risk reduction. To eliminate the risks, the designers can suggest solutions in the form of: 1. Inherently safe design measures, 2. Safeguarding and/or complementary protective measures & 3. Information for use.

Research in human-automation collaboration have highlighted a need to better understand human factors to design safe systems [4]. Norman notes that automation in itself is not the source of accidents but inappropriate feedback [17]. Academic literation points at two kinds of issues that can lead to an accident: 1. An operator looses track of the state at the machine and is referred to as situational awareness [22]. 2. In complex system with several mode of operations, an operator may lose track of the mode of operation and continue working with the assumption that state has not changed and this is referred to as mode-error [21].

2.2. Research approaches

Industry-as-laboratory [19], proposes that researchers can formulate questions through case studies of real systems to gain insights into problems of interest. Within the UIC framework, this approach can benefit researchers who are attempting to generate knowledge by identifying gaps in academic literature.

There are well-established research approaches that aims to generate knowledge from the change process itself. Action research (AR) and its variant participatory action research (PAR) [28] supports researchers in the learning process where the main agent for change is the researcher. PAR emphasizes collaboration between participants and researchers. The interactive research (fig 1) approach proposes that research activities such as selection of methods & tools for analysis need to a collaborative endeavor between all participants [16].

As noted by Svensson et al. [23], Interactive research (IR) stresses the joint learning that goes on between the participants – which include the researchers – throughout the entire research process, from the definition of the problems to the analysis as well as dissemination. Svensson et al. [23] states key features of IR, which are: 1. Unlike AR, participants own the change process. 2. Continuous joint learning between the researcher & the participants. 3. Participants with different perspectives stress on different aspects. 4. Inclusion of the participants in the whole research process can increase research validity.

![Fig. 1: Illustration of roles & interests of the participants and researchers in an Interactive research approach. Adapted from Svensson et al. [23].](image1)

![Fig. 2: The interactive process of Design Research Methodology (DRM) adapted from Blessing and Chakrabarti [2].](image2)

Design Research Methodology (DRM), proposed by Blessing and Chakrabarti [2], aims to provide rigor in design research. The methodology involves many iterations and parallel execution of the following stages (Fig: 2): 1. Research Clarification – The researchers try to formulate research goals based on the current situation based on literature review, interviews etc. 2. Descriptive Study I – The researchers attempt to make a detailed description of crucial factors that describes the current situation. 3. Prescriptive Study – The aim is to develop methods to realize the desired situation. 4. Descriptive Study II – the main focus is the application and evaluation of the previously selected methods.

3. Demonstrator Based Research – A Methodology for Collaborative Research

Figure: 3, outlines the demonstrator based research methodology. To understand prelevant issues associated with safety, a current assembly station, can be selected, as a case study. A case study can be defined as an empirical method aimed at understanding a contemporary phenomenon in their context [29]. A unit of analysis helps the researchers to describe various parameters that can explain the nature of the phenomenon being investigated. During the initial
phase, various methods can be used by the investigators to determine parameters that describes the current situation. Data can be collected through: 1. interviews [14] 2. observation 3. Academic literature 4. Safety standards as well as 5. safety training.

Demonstrators can be defined as a method to showcase design intent within a collaborative environment. Demonstrators can be visualized in many forms such as scaled models, computer aided virtual simulations, prototypes etc. The best-suited method for the application is chosen by the investigators to communicate features and characteristics of a system or subsystems. Gopinath and Johansen [7] details a functioning mock-up of a hand-guiding tool, where the requirements was formulated through the application of risk assessment and risk reduction strategies. That is, risk assessment (RA) coupled with product development strategies can be used to investigate and conceptualize probable solutions that describes desired outcome. As noted by Blessing and Chakrabarti [2], this process overlaps with the initial phases in order to reformulate the goals and methods, and establish a clearer picture of the desired situation.

The final demonstrator(s) represents the cumulative result of a series of research activities meant to effectively communicate the design intent of the desired outcome. It should showcase the solutions to the problems that was identified through the earlier stages, and allow probable users to evaluate the results by interacting with it.

The following section describe a demonstrator developed to showcase safety solutions of collaboration operations involving large industrial robots.

---

**Fig. 3:** An outline of the demonstrator based research methodology, developed for research in industrial safety within a collaborative environment

---

**Fig. 4:** Description of the sequence of tasks from entering the robot workspace, hand-guiding the robot, assembling the flywheel housing cover and starting the next work-cycle [6].
4. Case Study – Hand-guided Assembly of Flywheel Housing Cover (FWC)

Figure 4 shows the assembly process of the FWC on the engine block. The sequence of events are: 1. The robot begins the cycle in automatic mode and waits at the hand-over position after picking up the FWC. The light curtain is muted. The red light, which signifies that the robot is moving automatically and is not safe to enter, turns green. Green light conveys that hand-guiding motion can be activated. The operator enters the fenced zone to imitate the hand-guiding motion. 2. To begin the hand-guiding motion, the participant needs to engage both the three-position enabling device. They are integrated into the hand-guiding tool as shown in fig 4 (2) and is in a engaged state in the middle position (Annex C in [25]). When engaged, the robot can be moved simply by moving the tool. For the purpose of the demonstrator, the motion were restricted to only linear motion in three directions. 3. The operator moves the robot towards the engine block, aligns the two pins (not shown) before mating the two surfaces. After the clamps are removed, the participant needs to guide the robot back to the hand-over position. 4. The operator engages the three buttons together to convey the hand-guiding operation is complete. After exiting the robot workspace, engages the auto-contnue button which un-mutes the light curtains. The green light turns red and the robot is in automatic mode and begins the next cycle.

5. Evaluation of hand-guided assembly of Flywheel Housing Cover (FWC)

This section briefly details the results of a pilot study meant to evaluate the hand-guided collaboration workstation from the perspective of manufacturing engineers and operators.

5.1. Interview methodology

A pilot study with six personnel (two groups) participated in the study. Each group was scheduled one day and was encouraged to ask questions to the researchers as well as their colleagues. The participants represented two organisations representing the automotive and aerospace industry verticals. The three participants from company A had worked in the manufacturing industry with experience ranging from heavy vehicle assembly, robot programming and managing day-to-day operations of assembly lines. The three from company B represented the aerospace industry were responsible for design, requirement specification and installation of production cells. None of the participants were responsible for safety and have not tried to hand-guide an industrial robot.

The agenda for the day is as follows: 1. The researchers presented each group a brief summary of collaborative operations, requirements of safety along with information on what they will experience during the day. 2. The researcher demonstrated the hand-guiding collaboration operation in full as shown in figure 4. The researchers also discussed the safety equipment such as functioning of the light curtains and the enabling devices. 3. The participants were allowed to try out the hand-guiding operation in order to get accustomed to manipulating a large industrial robot. After they have tried out the full sequence, they were interviewed individually and were digitally recorded with their permission. The semi-structured interviews took approximately one hour and participant were encouraged to elaborate on their answers.

5.2. Discussion on Safety

Workspaces and safeguarding – The participants agreed that a well-defined workspaces – in terms of robot, collaborative & operator workspace – is an interesting approach considering the size and reach of the robot. Additionally, the participants commented that safeguarding measures (fences & light curtain) seems adequate though two participants commented on the fences being too tall (standards regulate the safeguarding height). Based on their observation of the layout, safeguards and task sequence, the participants commented that 1. the size of the robot is not a significant parameter and 2. the robot was over specified in terms of its payload \((\text{payload} = 210 \, \text{kg})\) as the FWC and the tool had a combined weight less than 50 kg.

Visual Indicators – The participants agreed on the importance of visual indicators to avoid hazardous situations. Floor markings and warning lamps were used to inform operators of the state of the system and its boundary. Three of the six participants commented on the current choice of warning lamp (One lit area that can change colors) and
suggested 1. stack lights (lights that have separate lit areas with different colors) and 2. floor illuminated solutions. The reasoning was that some people have trouble differentiating colors and prefer to focus on separate regions of a lamp post (similar to traffic lights). Therefore, stack lamps can avoid confusion. Also, they mentioned that a red color signifies an emergency situation where all operations are stopped and personnel in the plant need to follow emergency procedures.

Physical Interfaces – An emergency button and its location is a requirement in the safety standard. When questioned about the location, four participants stated that they did not observe it and needed to confirm its location. The participants agreed with the need for a three-step button on the hand-guiding tool to eliminate unintentional robot motion. The participants questioned the need for this measure on both the handles. They commented that one three-step button is adequate to maintain situational-awareness and it was difficult to engage and maintain both the buttons. After the participant returns the robot to the hand-over position, they have to perform two safety-related operations. 1. The three button switch to signal that the hand-guiding motion is complete and 2. The auto-continue button to signal that the robot can start the next cycle. The participants had mixed views and commented that only the second operation is required. The three button switch is difficult to use and can be avoided by using a safety scanner to monitor the workspace.

Safety Responsible – The interfaces were designed to give the participants full control of the station but their use needs to be complemented by additional safety sensors thereby reducing the responsibility for safety from the participants. The participants had different views and understanding on the question of who needs to be responsible for safety. For the aerospace industry, where the production rates are significantly lower than the automotive industry, one of the participant commented that it might be acceptable in certain special cases to have an operator responsible for certain aspects of the safety system. The participant also mentioned that the designers need to eliminate hazardous situations and good documentation along with safety-training can also help avoid accidents.

5.3. Hand-guiding operation

The participants from the automotive industry were familiar with the current manual station in the assembly plant and agreed that hand-guiding operations can improve ergonomics. Regarding the hand-guiding tool, the participants commented on the following issues:

1. It should be easier to engage the enabling device as it was easy to lose the grip while moving the robot (this stopped robot motion). They also commented that they additional training and redesign is required.

2. The handles should be designed to allow clearer view of the assembly point. The current design forced the participant to stand behind the housing cover that made it difficult for shorter persons to clearly see the assembly point.

3. The requirement to engage two three-step button to move the robot is cumbersome compared to when they tried to move without the three-step button.

Considering these issues, the ease of the system is acceptable for most participants. They commented that it was interesting that they can move very heavy or light objects with same force and there were no reactionary forces on their body. Five of the six participants commented that in order for this system to be usable, it should be possible to adjust the speed of the hand-guided operation (The maximum speed was limited in the laboratory environment). Two of the participants, after trying out the demonstrator commented that it allowed them to consider various instances within their organisation that can benefit with hand-guided industrial robots.

6. Discussion

This section discusses the methodological approach to the development of demonstrator and the interviews that were carried out to evaluate the design decisions that resulted in the hand-guided robotic system.
6.1. Methodological approach to collaborative research for industrial safety

As noted in section 1.1, the laboratory demonstrator described in section 4 was developed in collaboration with members from the industry, academia and research institution. A central principle in the interactive research (IR) approach is the active involvement of participants in the change process. The change process, which in this study, is the introduction of an industrial robot in a manual assembly station. Several members from the organisation actively participated in realizing this change. Some of the activities were: 1. defining goals and targets, 2. data collection and interpretation, 3. method selection & 4. requirement analysis. Lack of expertise within the core research group were complemented by experts such as those knowledgeable in interpreting regulatory standards. In a traditional way of conducting research, members of the academic institutions are the main actors (see chapter 2 in Nielsen and Svensson [16]). The activities mentioned above would have been performed by researchers, might result in industrially viable solutions, but the learning outcomes are limited to the researchers. Therefore, research within a UIC context carried out through a IR way, joint learning is a natural outcome.

Risk assessment is a methodology that enables standardized reasoning and evaluation of risks and allows the participants to document them in a systematic manner. Additionally, it allows for risk reduction measures, as discussed in section 2, to be prescribed, which should result in changes that mitigates the risks associated with known hazards.

6.2. Evaluation of the demonstrator

A qualitative analysis of semi-structured interviews (Appendix A) is detailed in section 5. The study was designed to evaluate the design decisions taken by the investigators during the research process. One probable outcome of a qualitative study is to gain insights into issues that require a detailed study. The interviewees indicated certain preferred techniques such as floor illumination and stack lights, which must be evaluated for standard compliance. The feedback on design changes such as physical design, hand-guiding response etc., needs to be analysed for usability and ensure that they do not introduce additional hazards.

7. Conclusion

This article presented a methodological approach that was used to develop a physical demonstrator to showcase safety-solutions of collaborative operations with large industrial robots. The results show that by involving personnel with multi-disciplinary perspective in the whole research process can result in viable solution relevant for the manufacturing sector. The physical demonstrator represents the cumulative result of a series of research activities undertaken with the intention of introducing a robot in a populated work environment in a safe way. In addition to the methodology, results of interviews that were carried to evaluate the demonstrator are also presented. The result of this pilot study, comprising of personnel from the manufacturing industry, indicates that the presented solution is viable and beneficial to their organisation.

Acknowledgements

This work has been primarily funded under the FFI program by Vinnova & the authors would like to graciously thank them for their support. We would like to thank the members of the research project Collaborative Team of Man & Machine (ToMM 2) for their valuable input & suggestions.

Appendix A. Interview Questions

Questions asked to the participants during the pilot study on 15-February-2017 & 24-April-2017.

Introductory Questions: (a) How long have you been working at your company and do you have experience working with industrial robots? (b) What are your reflection on safety based on what you have seen in the lab? (c) What are your reflections on the size and speed of the robot? Do you think that the size and speed matters when it is in the automatic or collaborative mode?
Questions on Safety: (a) What are your comments on the layout in terms of robot, collaborative and operator workspace? (b) During the demonstration, you had to go inside the robotic workcell and hand-guide the robot out of the cell? Do you think that it is okay for the robot to be coming out the cell? Was the collaborative workspace marked adequately? (c) Did you notice the emergency button? Was the location proper? Please comment on interfaces (lights, signals)? (d) How much responsibility can operators have? Is it better for the operator be responsible or sensor controlled? Or both.

Questions on Hand-guiding and the tool: (a) What are your overall impression of hand-guiding and do you think being in control is important? (b) Do you think additional training is needed? If so, how much?

References


