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Supporting risk assessment of human-robot collaborative production layouts: a proposed design automation framework

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Abstract

As fenceless human-robot collaborative (HRC) production layouts are developed as a viable alternative to traditional set-ups, risk assessment of such installations becomes highly complex. The involved risks include new challenges in the form of previously non-encountered dynamic hazards, which demand innovative solutions to ensure human occupational safety.

This paper aims to investigate the application of design automation in providing means of incorporating risk assessment in the early stages of development of production layouts. The result is a conceptual framework for a decision support tool with which the safety aspects of an HRC application can be evaluated before installation.

Keywords: Human-Robot Collaboration; Risk assessment; Design automation; Knowledge-Based Engineering; High Level CAD template

1. Introduction

In recent years, Human-Robot Collaborative (HRC) layouts have been introduced as an alternative to traditional robot cells in industrial applications. This is a result of continuous advancements in industrial robot design [1]. Whereas a conventional layout traditionally isolates the robot from human operators by means of physical boundaries, collaborative systems aim to remove these barriers and combine the strengths of industrial robots with human cognitive and tactile abilities in pursuit of heightened productivity and an improved ergonomic work environment in industrial production and assembly lines [2,3].

Small robots, with limited speed and lift capabilities, may been seen as easily implemented in a collaborative setting requiring minimal safety measures, while medium-sized or large industrial robots likely require extensive use of limiting programming, safeguarding or complementary safety measures to meet the safety requirements. This does not imply that small robots are inherently safe by design. Whereas a robot lifting a small, light-weight object and slowly moving it may not be seen as hazardous, the recently released technical specification ISO/TS 15066 [4] describes that any robot handling sharp objects in a collaborative setting will lead to significant risks. It is therefore important to note that it is the application of the robot that defines the system as collaborative, and requires risk assessment to verify that an acceptable level of safety has been established [5].

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As the development of HRC systems causes new challenges regarding previously unencountered hazards, risk assessment of HRC layouts is considered highly complex compared to traditional robot cells rendering it more prone to errors. In addition, inexpertly executed risk assessment may inadvertently result in hazardous situations, which means that thorough verification of the obtained results by experienced and knowledgeable personnel is essential. [5]

Design of a production layout is a time-consuming process when addressing the safety concerning industrial robots. According to safety experts experienced in performing risk assessments in the Swedish automotive industry, a sector which traditionally makes heavy use of robotics in welding stations, risk assessment of traditional robot production layouts designed in-house may cost roughly between one and five days. Due to the nature of collaborative systems, risk levels are highly application-dependent. Any change in application, i.e. a change of product handled by the robot or a newly introduced tool such as a gripper, will therefore require re-assessment. This element of repetitiveness adds to the complexity of risk assessment for HRC layouts, underlining the need for cost- and error-reducing methods. In order to investigate if the assessment process could gain from a more digitalised method, the aim is to explore the application of design automation in providing means of incorporating and supporting risk assessment in the early stages of development of HRC production layouts.

Collaborative systems are estimated to flourish within 3 years according to industry experts, creating the need for a framework specifically for risk assessment of such systems to guarantee that safety requirements are met uniformly. Such framework must provide means to facilitate design and rapid re-design of layouts, detection of risks and objectively suggest applicable risk reduction measures. Since achievement of acceptable levels of safety is the ultimate goal, the quality of its results is of the highest priority. Reduction or avoidance of errors in both the design and risk assessment of HRC layouts is therefore of utmost importance for the conceptual framework proposed.

2. Background

Before any industrial robot system is put into operation, a risk assessment is required to be performed in order to ensure that all safety aspects have been taken into account, according to the Machinery Directive 2006/42/EG [6]. To adhere to the machinery directive, the harmonised standard EN ISO 12100 [7] describes risk assessment of general machinery, while EN ISO 10218, consisting of EN ISO 10218-1 [8] and EN ISO 10218-2 [9], does so specifically for industrial robots and robot systems. Application of these harmonised standards lead to the presumption of conformity with the requirements. Acting as guidelines, they describe risk assessment as a process consisting of hazard identification, risk evaluation and risk reduction, preceded by determination of limits of the machinery and followed by documentation. While not a standard, ISO/TS 15066 [4] depicts the current state-of-the-art in robot safety standards, and specifies operating limits complying with the requirements stated in EN ISO 10218. It describes four distinct operation modes, each demanding different safety factors to be taken into account and provides applicable hazard models.

Hazards are identified based on data describing known hazard sources and harm resulting from these described in standards [9]. The risk of a person coming to harm in a hazardous situation is described in EN ISO 12100 as a function of severity and probability, in itself a function of persons' exposure, occurrence of hazardous events and the possibility of avoiding harm [7]. By estimating each of these, an overall level of safety can be estimated. Based on these elements, methods such as Task-based Risk Assessment discussed in EN ISO 12018 and described in the United States standard RIA TR R15.306 [10], incorporate decision matrices through which risk levels can be derived.

Risk reduction aims to bring risks to an acceptable level and is described in EN ISO 12100 [7] as a 3-step method. Firstly, risks are most effectively reduced through inherent safe design, meaning removal of hazards. If this is not impossible, the second step is implementation of safeguards such as protective fences and sensory equipment or complementary protective measures such as delay devices. The third and final step, provision of information for use, is resorted to if risks cannot be removed adequately through either of the preceding steps. Safety level of control functions, controlling protective measures, can be quantified using Performance Level (PL) as defined in standard EN ISO 13849-1 [11], reflecting the probability of failure. The Performance Level required (PLr) can be calculated in a similar manner as the estimated risk level based on severity, exposure and avoidance.

3. State of the art

The aim of design automation, as described by Tarkian [12], is to "minimize repetitive and non-creative design activities" in design processes, similarly to automation in manufacturing, where industrial robots are utilised to achieve higher accuracy and reduce time-costs. As with HRC, the goal is not to automate the entire process, but rather to give engineers the time and freedom to make better use of their creativity and intuitiveness without being halted by routine-like tasks. Up to 90 % of all tasks can be seen as "routine-like" and "non-value adding", requiring little creativity [13].

Knowledge-Based Engineering (KBE), as described by La Rocca and Van Tooren [14], combines elements of artificial intelligence, computer-aided design (CAD) and computer science, amongst other disciplines. It has a diverse variety of descriptions, being subject to different interpretations depending on application [12]. The common denominator is however that automation play a key role. Verhagen [15] presents KBE as a methodology "intended to deliver engineering design automation in scenarios where the retention of knowledge is critical", while Tarkian [12] describes it more detailed as "automating non-creative design tasks by utilizing object oriented programming", focusing on reuse of geometry and information in order to enable design automation for multi-disciplinary optimisation (MDO).

High Level CAD templates (HLCt) are described by Amadori [16] as "building blocks of flexible and robust CAD models", and are intended to enable design automation by providing means of automatically and dynamically constructing CAD models utilising KBE, as visualised in Figure 1. Their strength lies in facilitating the reuse of information. In addition to geometry, HLCt's contain rule-driven parametrisation for morphological transformations of the geometry and reference information dictating how the geometry should interact with its surrounding context within a CAD model. This not only enables modifications to the shape of an object, but also topological transformations such as adding or removing of instances of these objects and control of their position within the context. The templates can also contain information not directly related to the CAD model yet useful for subsequent stages of the design process involving the CAD models. As the templates are created in the CAD system, these are easily maintained and kept up-to-date by the same engineers that are intended to use them. [16] Application of HLCt has been confirmed to eliminate repetitive work and reduce time-costs in conceptual design of complex systems such as transport aircraft, modular industrial robots and high-speed trains [16–18].

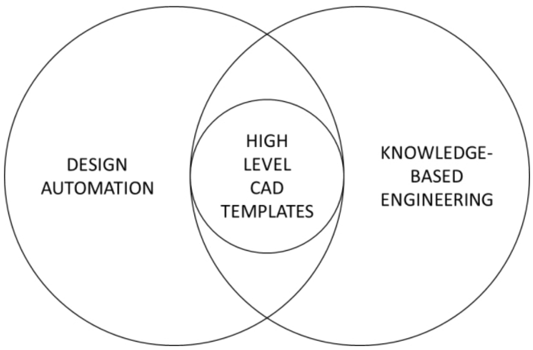

Fig. 1. Relation between High Level CAD templates, design automation and Knowledge-Based Engineering, based on Amadori. [16]

4. Method

The development of proposed the conceptual framework is based on review of literature describing the state-of-the-art concerning design automation and KBE and the application of HLCt, combined with data collected from literature and standards relevant to risk assessment of robots and robot systems. This is complemented with information gathered using semi-structured interviews and workshops providing an industrial view on the challenges and future status concerning HRC in industrial settings and risk assessment of these.

5. Result

5.1. Framework Proposal

The proposed framework for an automated risk assessment tool, intended to serve as a support decision tool to be used in the conceptual design process of HRC layouts, consists of three segments being layout configuration, a risk assessment cycle and subsequent generation of information as shown in Figure 2. It closely follows the lines of the process described in EN ISO 12100 with limit determination, hazard detection, risk estimation, determination and application of risk reduction methods through the 3-step method and documentation.

An initial layout configuration is designed using HLCt to create a static, 3D model, determining the limits of the system. A workspace and reach analysis is performed to ensure that all points of interest are within reach of robot and/or operator, and are within the appropriate designated workspaces. If the analysis returns erroneous results, the layout is re-configured before advancing to the risk assessment. Geometries' shape or position may be altered through morphological or topological alterations, or components may be added or removed, to achieve a satisfactory initial configuration.

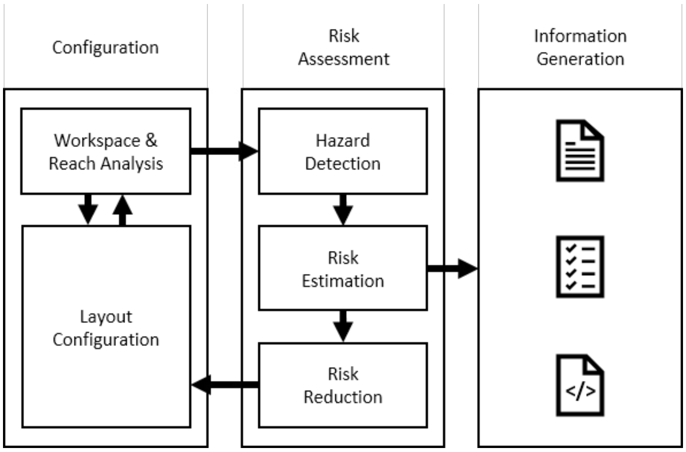

Fig. 2. Proposed framework for automated risk assessment of human-robot collaborative systems

In the first step of the risk assessment segment, hazard detection is automated in both static 3D models. In these models, distances between a robot's reach, operator workspaces and surroundings can be measured or sharp edges near operators can be detected. Adding a time element, 3D simulations building upon the statically configured CAD model can be used to dynamically detect hazardous events associated with movement of robots near operators.

From the detected hazards, the severity, exposure, occurrence and avoidance factors are calculated, resulting in a quantified risk level for each. The score is based on findings from the simulations, or can be estimated based on findings from the static hazard detection in combination with user-specified values for exposure and avoidance. If risks are deemed unacceptable, risk reduction measures are produced based on the risk estimation outcome. These come in the form of alterations to the original configuration, safeguarding and complementary protective measures. For the second, PLr is calculated based on results from the hazard identification. If a risk cannot be reduced to the intended level of safety, information for use is generated to be included in the documentation. The risk reduction modifications and measures are applied to the CAD configuration, at which point the process reiterates. Alternatively, the user may be presented with an advice package of configuration alterations and appropriate measures if human interaction is desired.

Once all risks are calculated to be within predefined acceptable limits, the risk assessment process is terminated and information can be generated. This includes detailed documentation on required safeguards and complementary safety measures and description of residual risks and application-specific manuals for operation and maintenance of the layout, which can be created based on predefined manual templates.

5.2. Required data

Layout configuration requires an HLCt database with templates for robot models, obstructions surrounding the layout, designated workspaces, operator models and safety measures. In addition, application models, i.e. the product to be handled by the robots, must be included. The templates for moving objects such as robots and operator models are required to include information regarding speed and direction of movement and mass, so that these can be simulated for identification of dynamic hazards. In addition, a knowledgebase dictating the logic according to which the HLCt are instantiated in a CAD model is required.

Identification of hazards requires a database of known, quantified hazard models describing for example minimum distances or maximum robot speeds with regard to operator proximity, based on the allowed values described in ISO TR 15066 and other standards. In order to be able to calculate risk levels, non-geometrical knowledge can be required to be included in the templates or stored in the risk database. Such information would include exposure details such as frequency of operation of the layout. Human behaviour models depicting typical reactions to hazardous events will be necessary to accurately estimate the possibility of avoidance of harm.

For risk reduction, a database is required containing information concerning geometric modifications proven to be beneficial to the layout safety, such as relocation of robots or modifications to other tools or the product, as well as information concerning the applicability of safeguards and complimentary safety measures included in the HLCt database based on the required performance levels.

6. Discussion

The proposed framework requires a significant investment in the form of preparation time. However, once the framework is in place and the hazard model, risk reduction and HLCt databases and associated knowledgebases have been populated, the framework will be able to render results quickly and consistently, reducing the chance of sporadic errors compromising the safety of the designed layouts. With that said, it must be noted that the framework relies on human input and verification, meaning that errors in the knowledge- and databases will still result in flawed safety designs. Ultimately, the aim of the framework is to improve the quality of risk assessment outcomes by relieving engineers of tedious, unintuitive elements of the process and allowing them to use their creativity and focus on the essentials, without automating the entire process.

Initially, all stages described in the framework can be controlled manually, while only basic repetitive tasks are automated such as instantiation of templates during the configuration phase and compilation and ranking of applicable risk reduction measures during the risk assessment phase. Once the framework is proven to produce satisfactory results, the process can be iterated using optimisation algorithms, minimising manual effort in initial layout configuration and verification of results. For hazard detection, artificial intelligence models may be used to simulate the effects of human reactionary behaviour on the outcome of hazardous situations. Knowledge on unexpected, possibly hazardous situations, either simulated or from previous operations, may obtained using knowledge processing systems such as KnowRob [19], integrating feedback from robots themselves into the risk assessment.

Notably the possibility of quickly iterating through configurations may be a valuable tool by itself during the conceptual stage of layout design. As risk assessment is hindered by redesign of layouts, acceleration of this process may be beneficial to the risk assessment process, even if risk assessment is done manually. Integrating risk assessment early in the conceptual stage of the layout design process allows layout designers to prioritise inherently safe design over secondary safety measures, thereby following the 3-step method as described in EN ISO 12100. The use of HLCt creates a streamlined process where the designer is free to include any applicable machinery, safeguards or other components, meaning that any type of robot layout, both collaborative and traditional solutions, can be configured for subsequent risk assessment. The freedom to reconfigure and update a layout designed using HLCt allows for reassessment even after the design has been implemented, in the event of a change in application of the HRC system, meaning that the tool can be used throughout its lifespan.

7. Conclusion

It is concluded that there is a need for a decision support tool that streamlines the risk assessment process of conceptual HRC production layouts, and reduces occurrence of errors early in the design process resulting in safety concerns. This conclusion is drawn from the notion that no robot system can safely be considered collaborative without expertly performed risk assessment, and that the quality of risk assessment of HRC systems may be jeopardised due to their complexity.

A conceptual framework is proposed, attempting to show that automated risk assessment of HRC production layouts is possible using design automation achieved with the help of KBE. It utilises the HLCt methodology to facilitate rapid configuration and reconfiguration of layouts, of which risks are automatically assessed to provide a package of feasible risk reduction measures, both in the form of alterations to the setup as well as addition of complementary components. This framework depicts a decision support tool producing consistent and objective results, thereby improving the quality of the risk assessment. It is seen as highly important that any use of the tool and verification of results must be carried out or supervised by experts within the field of safety of machinery, to eliminate any safety concerns caused by erroneous input or interpretation.

8. Future work

In order to verify the feasibility of the proposed framework, a proof-of-concept configuration tool with HRC-specific HLCt templates must be developed to benchmark its impact on current layout design and lead times. In addition, the translation of HRC safety requirements to quantified design knowledge is to be explored, resulting in a database of hazard models and risk reduction measures. To validate results, the time-costs of risk assessment of HRC layouts must be measured and compared to results from the framework once a functional proof of concept has been development.

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