Safety of Human-Robot Collaboration within the Internet of Production

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Abstract. Recent trends in globalization have led to an increased competitive pressure, particularly affecting the manufacturing industry. The Cluster of Excellence "Internet of Production" (IoP) aims at developing innovative solutions and reshaping production to enable local industries to thrive in a digitized world. These developments create new possibilities for Human-Robot Interaction (HRI) and Human-Robot Collaboration (HRC) in particular. An extended framework for the classification, analysis, and planning of HRI use cases within the cluster IoP was developed, whereby examples from preforming and assembly were introduced and classified. Due to their collaborative nature, these cases require high safety standards that protect the human from the cobot. This paper describes how the cluster IoP handles safety of human workers in HRC processes, which allows a shift towards an increased collaboration between humans and robots. In this context, this paper proposes different methods to increase safety in HRC applications. This includes the use and verification of Behavior Trees for process planning and execution, the application of Computer Vision, the design of safe robot tools, and the evaluation of human acceptance and trust.

Keywords: Human-Robot Collaboration · Safety · Behavior Trees

1 Introduction

The use of industrial robot systems that interact with humans paves the way for an increased flexibility in production. Furthermore, new methods of data acquisition, processing and modeling enable new possibilities for human-robot interaction (HRI) and in

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particular human-robot collaboration (HRC). These developments are especially driven in the Cluster of Excellence research project "Internet of Production" (IoP) [1]. A focus lies on transferable and interdisciplinary research between researchers from domains such as mechanical engineering, computer science and ergonomics. As a comparison, HRC is a research field that comprises knowledge from many different expert fields as well.

Baier et al. developed an extended framework for the classification, analysis and planning of HRI use cases, in order to support the human-oriented work system design of next generation production plants [2]. This included the analysis of use cases from HRC. Despite the continuous growth of the market for collaborative robots (cobots) [3], the industrial use of cobots is still marginal, especially for small and medium-sized businesses (SMB), which is mainly due to the strict regulations that aim to protect humans during collaboration.

Therefore, we collect current methods for safety of HRC processes within the cluster IoP in this work that are cost-efficient at the same time. This first includes the use of inherently reactive Behavior Trees (BT) and their verification. We use a verification method for BT that verifies safety properties in the program code and thus can eliminate possible errors. The BT semantics and error checks are therefore encoded in a collection of logic formulas, which in turn are verified by an existing verification algorithm. Furthermore, a Speed and Separation Monitoring (SSM) system can be integrated into a BT architecture in addition to the Power Force Limiting (PFL) function of the cobot using cameras and Computer Vision (CV) to detect the human hand. We outline how the given standards and guidelines can be integrated into the development of robot tools for new working environments as well as identifying deficits. Finally, approaches to improve the confidence range from visual indicators to anthropomorphic robots will be discussed in this paper.

This paper describes a cluster IoP-centered take on safety for HRC. Since the cluster IoP conducts research in close cooperation with the industry, this paper aims at bridging the gap between research and industry. For this purpose, two industrial use cases are presented and used for demonstrating safety regulation checks. The structure of this paper is as follows: In Sect. 2, current safety regulations regarding HRC are summarized. Section 3 shows the industrial use cases and their classification according to the extended framework. This is followed by a survey of safety concepts within the cluster IoP and a safety check for the presented use cases in Sect. 4, before finishing with a conclusion and outlook (Sect. 5).

2 Safety in Human-Robot Collaboration

According to data from the German, Austrian and U.S. labor unions, more than 55% of human injuries inflicted by robots affect the human hand, see Fig. 1. This data does not include collaborative robotic cells; however, the data shows most of the accidents between humans and robots occur due to clamping and crushing [16]. Since more than half of these accidents affect the hand, it is likely that most accidents in HRC affect the hand as well.

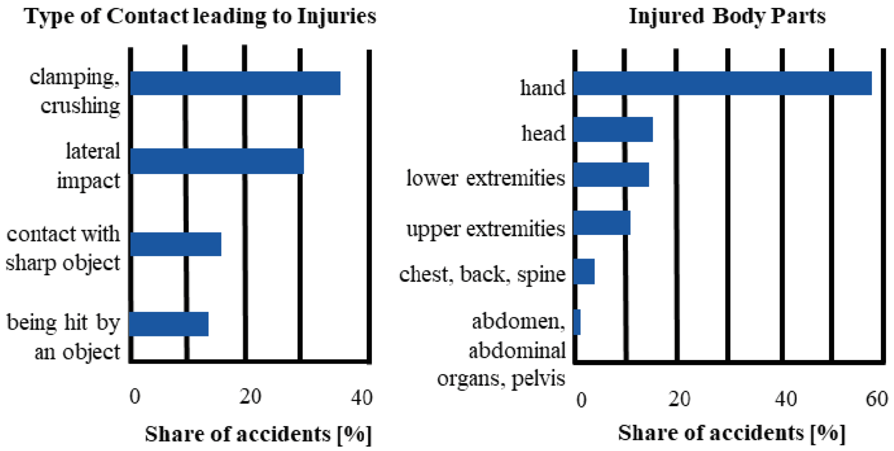

Fig. 1. Injuries depending on type of contact (l) and body parts injured by robots (r) [4].

2.1 Collaborative Safety Regulations

In 2010, the European Union developed general design principles for machine safety, risk assessment and risk reduction, called DIN EN ISO 12100:2010. It replaced its precursor DIN EN ISO 12100:2003. The main purpose of this new international standard within the European Union is to provide designers and engineers with an overview and guidance for decisions to be made during the development of machinery and to enable them to design machinery that is safe for its intended use. In DIN EN ISO 12100:2010, machine safety is defined as the ability of a machine to carry out its intended function(s) during its lifetime with the risk being sufficiently reduced. To reduce the risk sufficiently, the designer or engineer must apply a risk assessment and risk reduction scheme. This scheme consists of [5]:

1. Considering the safety of the machine in all phases of its life cycle (most important).
2. The ability of the machine to perform its function (very important).
3. The ease of use of the machine (important).
4. The manufacturing, operating and dismantling costs of the machine (less important).

In 2020 and 2021, the European Union developed DIN EN ISO 10218-2:2020 and DIN EN ISO 10218-1:2021 about safety regulations regarding industrial robots. The first part is about industrial robots in general, the second part is about their applications and industrial robot cell integration. The aim of both norms is to lay the foundation for safe construction of protective measures and to provide information for the safe use of robots in industrial environments [18, 19].

According to the first part of the norm, control systems must be designed in a way that a reasonably foreseeable human error during operation does not lead to hazardous situations. If the robot starts acting unexpectedly during a failure in the control system, there must be a protective measure to counteract harm for workers. Additionally, the robot system must provide a controller, programming pendant or external control as well as the corresponding connectivity. Furthermore, there must be a limit to the range of the robot which cannot exceed the maximal workspace that is reserved for the robot [6].

In industrial HRC, the human must be protected from the (moving) robot and the product the robot carries. If possible, sharp edges, which could harm the human must be reduced [7]. There are four different possibilities to ensure a safe HRC [8]:

- Hand-guided Control
- Power and Force Limiting (PFL)
- Speed and Separation Monitoring (SSM)
- Safety rated Monitor Stop

Hand-based control means the robot is only moving if the worker physically moves the robot with his/her hands. If the human is protected via PFL, the limits for power and force must be set beforehand. If a sensor in the robot measures a force above the defined threshold, the robot must perform an emergency stop. Another way to protect human beings is the implementation of an SSM system. The SSM system must reduce the speed of the robot if the distance between worker and robot falls below a certain threshold. Additionally, the SSM system can change the trajectory of the robot to keep a minimum distance between the worker and the robot. The safety rated monitor stop stops the robot as soon as the worker enters the workspace of the robot [8]. Therefore, the worker and the robot are not able to work together on one product in the same cell at the same time.

2.2 Risk Assessment and Reduction

Carrying out a risk assessment and risk reduction, the designer or engineer must proceed iteratively in the following order [5]:

- Defining the limits of the machine, including its intended use and reasonably foreseeable misuse.
- Identifying hazards and associated hazardous situations.
- Assess the risk for each identified hazard and hazardous situation.
- Assess the risk and make decisions about the need for risk mitigation.
- Eliminating the hazard or reducing the risk associated with the hazard through protective measures.

The risk related to the hazard under consideration is a function of the damage, which could arise due to this situation as well as the possibility that this situation will occur. The possibility that this hazardous situation will occur is itself a function of the hazard exposure, occurrence of a hazardous event as well as the possibility to avoid or limit the damage. Figure 2 visualizes this context [5]. For the long-term safe operation of a machine, it is important that the protective measures enable the machine to be used without disturbances. Additionally, the protective measures must not impair its intended use. The risk assessment must consider the possibility that protective measures can be rendered ineffective or circumvented. The designer or engineer must also consider that there may be an incentive to render protective measures ineffective or to circumvent them [5].

In 2015, the European Union published DIN EN ISO 13849-1:2015. It lays out the general principles for the design of safe control systems. There are different ways to reduce the risk of a hazard situation. The risk can be reduced by mechanical protective measures such as protective algorithms or by electrical protective measures. Before reducing the risk, the average probability of a dangerous failure is determined. If the value is standardized to one hour, the value is called performance level. There are five different performance levels ranging from more than 10^{-5} failures per hour to less than 10^{-7} failures per hour [9].

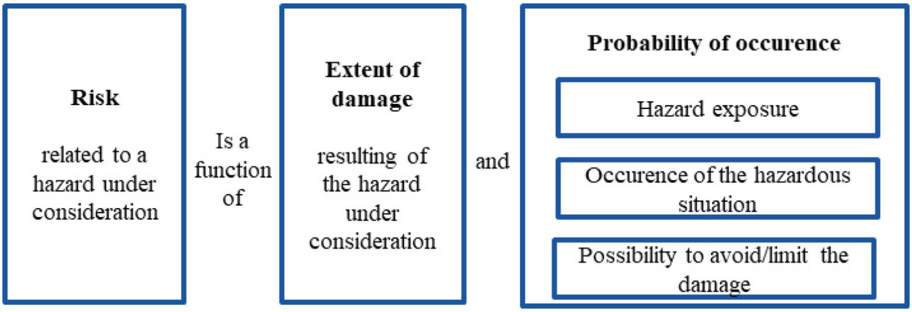

Fig. 2. Risk is a function of extent of damage and its probability of occurrence [5].

2.3 Software Safety Lifecycle

For the software safety lifecycle, a simplified V-model is used to ensure the reliability of the algorithm, see Fig. 3. Hereby, the software is designed gradually starting from the safety-related specifications of the algorithm. After each step, the system/module/code is verified to ensure the reliability and safety of the software and its integration into the system [9]. DIN EN ISO 13849-2:2012 is about the validation of safety-related control-systems. The validation of the safety functions aims to demonstrate that the machine or control system performs the safety function(s) corresponding to the specified properties. This is achieved by an analysis, which includes [10]:

- The structure or architecture of the system.
- Deterministic arguments.
- Quantifying aspects (e.g. average time until failure).
- Safety functions identified during the risk analysis, their properties and the required performance level(s).
- Qualitative aspects which influence the system behavior.

The analysis can either be performed top-down or bottom-up. [ISO12].

3 Classification of Two Use Cases Within the Cluster IoP

Two exemplary use cases of HRC within the cluster IoP are presented and classified using the extended framework as proposed in [2] to identify the kind of HRI and the characteristics of the systems used. This analysis is important in terms of safety, so that

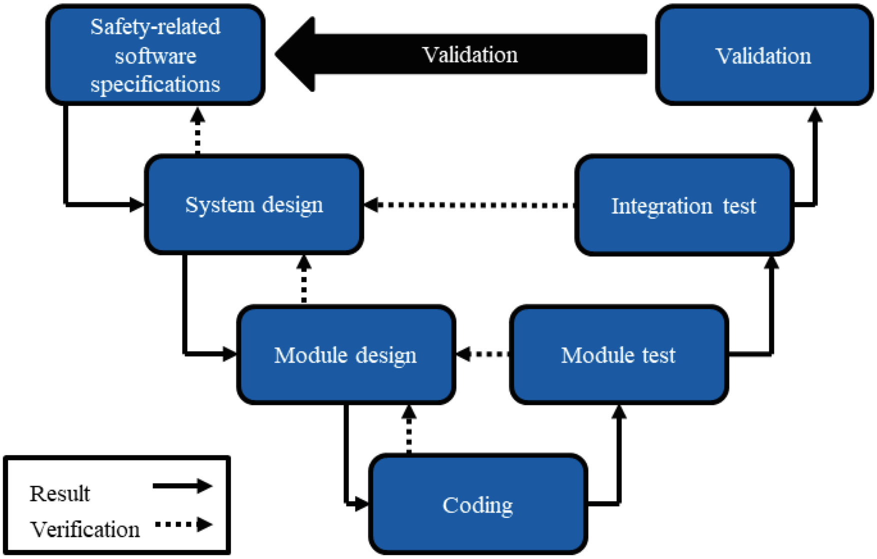

Fig. 3. Simplified V-model for safe software [9].

it is clearly shown where there are contacts between humans and robots, what risks exist and which resources (e.g. sensors) are available to counter the risks or generally increase safety.

3.1 Classification of Human-Robot Interactions

For the classification of the HRC use cases, the framework according to Baier et al. [2] is used, which was developed for the cluster IoP. Figure 4 shows the use cases described in this paper. This framework allows both the analysis and the synthesis of an HRC application, based on three dimensions: (1) On the horizontal axis, the degree of overlap of the workspaces is plotted. This ranges from completely separated to partially overlapping and to connected to the body. (2) The dimension "precondition and implication" forms the interface of the HRC system to its subsystems. Here, the question is, which preconditions exist and which implications the HRC system possesses in the social, legal and technical domains. (3) Since the IoP project focuses on the collection, processing and use of data at distributed locations, this requirement is mapped in a separate dimension. A distinction is made as to whether the data originates from sensors that are either attached to the device itself or supplied by external sensors, or whether it is available as a digital shadow. A digital shadow is the digital representation of an artifact (product or process) through a set of selected properties (see [1] for more details). Figure 4 illustrates the application of the classification scheme based on the two use cases described in the following.

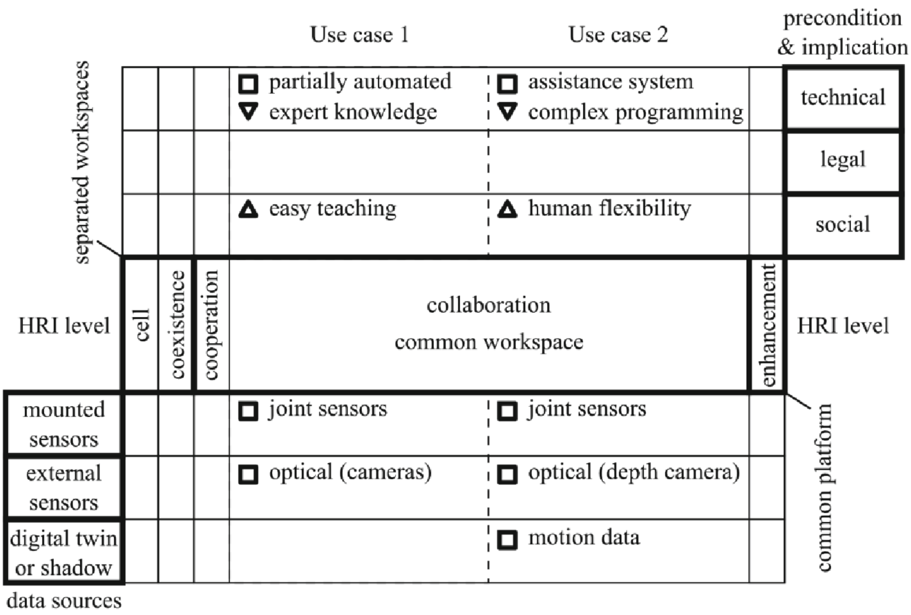

Fig. 4. Exemplary classification of use cases 1 and 2 with a selection of properties on the basis of [2] with adapted visualization to display the use cases side by side. Legend: △ positive, ▽ negative and □ not evaluated.

3.2 Use Case 1: Collaborative Assembly of Multi-variant Products

The trend towards multi-variant and customer-specific products as well as the shortening of the time to market requires an increased flexibility of the production process. Assembly is particularly affected by this due to its proximity to the market as the last production step. Collaborative assembly, which combines the advantages of manual work (flexibility and dexterity) and automated work (efficiency and quality advantages), offers potential for optimization. A disadvantage of automation is the necessary expertise, which SMB often lack.

When planning and implementing collaborative assembly processes, two aspects are particularly relevant: flexibility and safety. On the one hand, uncomplicated adaptation of the process must be possible in the event of changes, without the need for a robotics expert. The majority of robot manufacturers such as Franka Emika GmbH or Rethink Robotics Inc. Offer graphical user interfaces that replace code-based programming. Process planning was further simplified by Land et al. [11] using a simulation-based framework and, for example, a method for automated planning based on reinforcement learning was developed in [12]. Collaboration as the highest level of interaction between humans and robots (shared workspace as well as activity) requires strict safety standards. In [13], the internal safety functions of a cobot are augmented with external sensors and camera systems to prevent collisions between humans and robots while maintaining process efficiency. An algorithm has been developed in [14], for example, which can compute trajectories in real time to avoid obstacles.

The methods currently developed often represent isolated solutions that are not directly applicable to every type of robot. Furthermore, in most cases an extension by further functions requires a complex adaptation of the overall system.

In the project “CoboTrees” within the cluster IoP, BT are developed for the manufacturer-independent optimization of collaborative assembly processes while complying with safety standards at the same time [15]. The validation use case of collaborative assembly of a lamp can be seen in Fig. 5. It shows steps that can easily be done by the robot such as fastening screws but also handling of cables, which requires the dexterity of the human.

Classification. *HRI Level:* Due to the parallel manufacturing of the product by human and machine in the same workspace, this is classified as a collaboration.

Preconditions and Implications: The process can be partially automated, although individual work steps must be performed by humans. This applies in particular to the flexible cable. Expert knowledge is required to program the robot, whereas teaching is possible without prior knowledge.

Data Sources: The primary data sources used are externally mounted cameras that optically record the work process. In addition, the torque sensors installed in the robot joints are used for safety purposes by detecting unexpected forces and bringing about an emergency stop. The gripper is HRC-capable but with no dedicated sensors. A Digital Shadow is not used in this use case.

Fig. 5. Demonstrator for collaborative assembly of a lamp.

3.3 Use Case 2: Collaborative Production of FRP Parts

Due to their excellent mechanical properties combined with lightweight, Fiber-Reinforced Plastics (FRP) are used in high performances applications such as aviation, automotive, wind energy and sporting goods. At the moment, around a third of all FRP parts worldwide is produced manually [16].

On the one hand, this is due to the fact that in manual FRP production the workers' sensorimotor abilities can be fully taken advantage of. In addition, rapid product changes are possible, due to the cognitive flexibility of humans as well as low machine and tooling costs. However, waste resulting from human errors, low production speeds and high wages are disadvantageous [17, 18]. On the other hand, the automation of FRP production seems promising in reducing manual process steps and increasing reproducibility. Large corporations in the aviation and automotive industry are already using special automation machines for the production of FRP parts. Yet, these machines are expensive and their implementation is elaborate which results in a lack of flexibility [19, 20].

In most cases, the existing demands regarding FRP part quality, low part costs, productivity and ergonomics of production cannot be fulfilled by existing production scenarios. Therefore, a semi-automated production of FRP parts is a promising approach [18, 21, 22]. In this use case (see Fig. 6), the collaboration of humans and robots is investigated to exploit both, human strengths (cognitive flexibility, dexterity, sensorimotor abilities) and robot strengths (high precision and speed).

Currently, robotic tools that are able to implement the collaborative production of FRP parts are not commercially available. Therefore, these tools are developed as part of the use case. The focus lies on compatibility with the limp and partly sticky textiles to be processed. Typically, cutting devices are used for FRP part production in addition to rolling and squeegee tools. Here, special safety requirements must be met in order to protect humans from being harmed within the process.

Classification.
HRI Level: The simultaneous handling of the product in the same workspace or the assistance of the robot during human handling constitutes a collaboration according to the classification scheme.

Preconditions and Implications: Due to the complex geometry of the part and unpredictable behavior of the limp textile material, human flexibility is irreplaceable. It is combined with the power and accuracy of the machine. In combination, this results in a shift in the scope of the human task. The complex programming of the technical system is a disadvantage.

Data Sources: In this case, the torque sensors built into the robot joints are used to interact with humans. They measure the forces acting from the outside and determine the direction in which the human wants to move the arm. Furthermore, they are used to define the forces with which the textile material is brought into 3D shape. In addition to the internal sensors, external depth cameras are used to detect the human and the workpiece. Motion data from the robot controller and videos of the workers' movements for saving human expert knowledge are output as digital shadows.

4 Safe Collaboration Within the Internet of Production

In this Section, different concepts that are currently under research and enable safe collaboration for the two classified use cases are presented. These include inherently safe BT and their verification, the use and integration of CV, safe end-effector design and implementation as well as the consideration of human acceptance and trust.

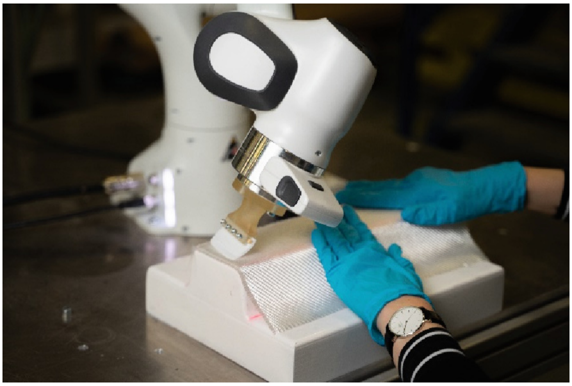

Fig. 6. Human-robot collaboration within FRP-part production.

4.1 Process Modeling and Execution Using Behavior Trees

BT are mathematical models of plan execution and widely used in the robotics community (e.g., in an unmanned aerial vehicle's control system [23]). They are reactive because of their tick-based execution [23, 24]. This allows interleaving of sensing and execution tasks. With every tick of the root node, safety branches are visited before ticking the execution node. Safety can be checked on a high level, where a "safety sub-tree" is the left most branch, i.e., ticked first.

BT synthesis approaches can create a tree in runtime from a given set of goals [24, 26, 27]. They start with a set of condition nodes, each representing a given goal and iteratively expand the tree to increase its region of attraction, i.e., the set of states from which the executing tree eventually returns success. These approaches do not focus on optimal execution but guarantee convergence. They are also able to expand the tree at runtime according to the environment, e.g., adding a branch to remove obstacles in the way before proceeding with navigation tasks.

We can also execute safety on a lower level by adding guards to the left of action nodes. Additionally, BT were combined with control barrier functions in a multi-agent system to guarantee that the tree completes a task under constraints (e.g., avoiding collisions) [25]. The tree in Fig. 7 checks whether sensors (e.g., camera) are active before executing tasks and later checks if a collision free delivery path exists before ticking the "deliver" node.

It is also possible to assure safety on the implementation level of BT nodes. Defects occur on this level due to the clear and intuitive representation of BT. The representation hides the exact implementation of actions and the control flow, which is implicitly defined. For example, in Fig. 7, it is possible, depending on the implementation, that after adding the screws the fastening step fails, which could lead to adding screws during the next tick although they are already in place. To prove the absence of these kinds of errors, different encodings of BT and their verification were presented [28–30]. These approaches often cover only a subset of nodes in a BT or need an additional input from the user, which are the semantics of actions specified in a certain logic. These restrictions prevent the simple use of verification methods by the user.

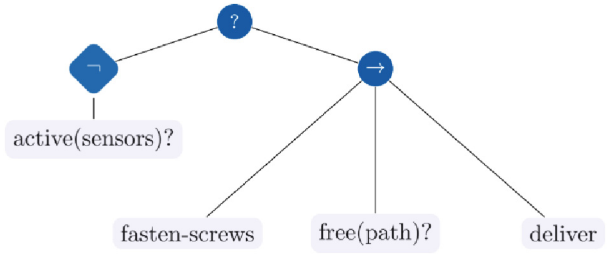

Fig. 7. A BT to assemble and deliver a desk lamp.

The presented approach from the cluster IoP [25], depicted in Fig. 8, allows the user to write the safety property as an assert statement using existing variables in the program. The assertions are part of the program code and therefore the checked safety properties are on a lower level than those presented in Sect. 4.1. Since the assert statements are only relevant for verification, they are removed before deployment of the system and do not impact the runtime behavior. The semantics of the added assert statements and the BT are automatically encoded as Linear Constrained Horn Clauses. In [25] an existing SMT solver is used to analyze the set of clauses and either obtain proof that the assertions hold for every execution or receive a counterexample which violates at least one assert statement.

The approach works independently of the actual system and environment. In order to analyze safety properties which depend on the environment, a facility is provided to implement the semantics of the environment as a BT, which is then combined with the BT of the system. The next step encodes the BT of the system and environment together.

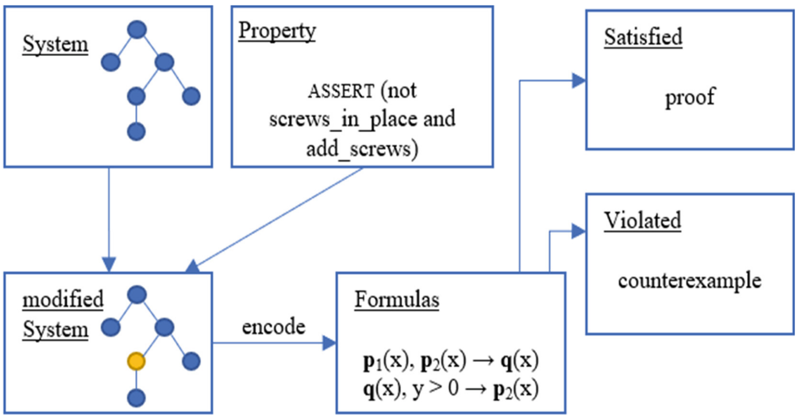

Fig. 8. Overview of proposed verification method for BT.

4.2 Application of Computer Vision

The previous section described a formal method to verify the safety of a HRC process. In order to react to dynamic changes, which mainly result from the unpredictability of the human worker, machine learning, or to be more precise, CV is proposed. CV is an interdisciplinary scientific field. It tries to process and analyze the images captured by cameras to understand their content (classification) or extract geometric information automatically (detection) [26]. In the case of HRC the latter is relevant for automatically extracting geometric information from an image to detect the position of a human being in the robot's work cell.

Since the majority of accidents occur on the human hand (see Fig. 1), we focus on CV algorithm capable of single hand detection. Many algorithms such as YOLOv5 and OpenCV. The YOLOv5 network uses bounding box regression and does not determine the exact (key) points of the hand [27]. The OpenCV hand detector on the other hand is already pretrained with more than 30.000 different images of hands [28]. Additionally, the algorithm allows for a high frame rate because as soon as a hand is detected, the algorithm searches in the local environment of the hand in the next image. A disadvantage is that the algorithm only outputs the evaluation of the hand position from an RGB image in 2D.

In use case 1, the OpenCV hand detection algorithm is integrated into the BT and tested on a real human hand. A detailed description and results can be found in [29]. The integration of the algorithm is structured according to the V-Model (see Fig. 3). After conducting the system analysis and requirements for the safety algorithm, a generic SSM system in ROS with an embedded BT is designed. The subsequent module design contains a camera module, which preprocesses and forwards the image of the camera into ROS, the detection algorithm and transformation module as well as the safety subtree. After the coding phase and testing of the individual modules, the whole system is tested. Here, the hyperparameters of the implemented algorithm are optimized, which need to be set by the engineer beforehand and depend on the robot and the environment of the robot. The stopping distance (minimum distance between hand and robot) is computed in order to meet DIN ISO 15066.

In the validation phase, the system shows high reliability for different hand gestures. The slow frame rate of 10 fps leads to a high value for the stopping distance to satisfy DIN ISO 15066, since only a CPU is used. Furthermore, the detection algorithm fails if the worker wears gloves (Fig. 9).

4.3 End-Effector Design

In addition to the use of BT for process planning and execution as well as the external application of CV, further improvement of safety can be accomplished through an appropriate design of the applied gripper. As stated in DIN 15066, different security measures are identified for distinct times of a contact phase. Here a pre-contact stage, the moment of contact and a post-contact stage are considered. Thereby, active security measures are identified to address the pre-contact phase, while passive security measures can improve safety within the stage of contact and the post-contact stage (see Table 1).

Fig. 9. Hand detection algorithm using OpenCV.

Table 1. Active and passive safety measures for end-effector design

Active safety measures (pre-contact phase)
Limitation of forces and torques by the Body Atlas
Limitation of cobot speed
External sensors to predict collisions
Passive safety measures (moment of contact and post-contact phase)
Increased contact area (rounded edges, smooth surfaces)
Compliant surfaces (padding, deformable components)
Reduction of kinetic energy through lightweight construction
Limitation of drive energy

Active security measures include limiting the maximum forces and pressures for cobots, which are derived from the Body Atlas found in DIN 15066 [8]. The Body Atlas divides the human body into 29 areas. For each area, biomechanical limits are described, each of which specifies the maximum pressure and force values that a body area can withstand without sustaining irreversible or major damage.

In addition, a distinction is made between two types of contact. Quasi-static contact (static clamping situation) describes a contact in which a part of the operator's body is clamped between the robot and another fixed part. In the case of transient contact, the body part that is hit can rebound from the robot (dynamic impact). The permissible contact forces are higher for transient contact because the person can escape the movement. Figure 10 shows an overview of the maximum forces and pressure loads for the quasi-static contact case.

Overall, the maximum cobot speed at which no damage occurs in the event of a collision can be determined from the prescribed pressure and force values in each case. Furthermore, additional sensors can be used to prevent collisions [8, 30, 31].

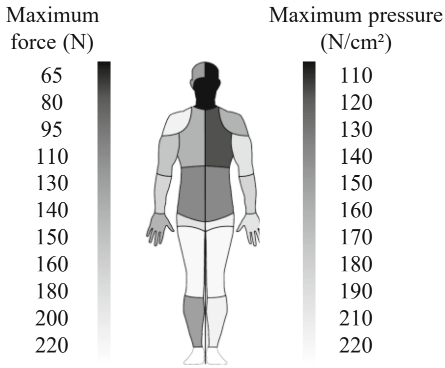

Fig. 10. Body Atlas showing the maximum forces and pressure prescribed in DIN 15066 [8].

Besides the discussed methods for safe collaboration through measuring, monitoring and control, passive approaches exist to reduce the risk of injuries solely through the mechanical design of the gripper. Thereby, the common injuries, as given in Fig. 1, can be addressed through different approaches.

First, contact with sharp objects and bruises can be avoided through an appropriate housing design. Sharp edges should be avoided, and functional parts of the mechanism must be protected in a way to prevent the possibility of bruises in general.

The risk of being hit by the gripper, as well as lateral impacts, clamping and crushing is mainly reduced by the presented approaches that try to eliminate the occurrence of dangerous situations at all. Passive security measures are applied for further support. In the case of occurring impacts, despite precautionary measures, resulting forces and thus the risk of injuries shall be minimal.

One possibility is the general limitation of forces. This can be realized actively, e.g. by controlling the applied tendon force in a tendon-actuated gripper, where the force should be dependent on the detected body part that is at risk of collision. However, passive realization is more reliable and robust in execution. It provides internal mechanisms that prevent the tendon forces from exceeding a defined level. This can be realized, by way of example, with any form of mechanical clutch. Although this approach does not allow to adjust the forces to different levels, considering the requirements of the Body Atlas, a standard value of 40 N for the whole gripper is accepted as the operation force comfort limit when operating with humans [32].

In contrast to generally limiting the applicable forces, other approaches solely focus on reducing occurring impact forces without necessarily limiting the grippers' overall performance. On the one hand, a reduction of the colliding mass by using light weight structures can be used to reduce the impact energy. On the other hand, compliant materials often are implemented.

The application of light weight structures is plausible, considering an imaginary scenario with being struck by a metal pipe versus being struck by a polymer pipe. The application of elastic materials, on the other side, does not effectively limit the occurring forces but allows to lengthen the contact phase and thus distributes the impact energy over a longer period, which consequently lowers the force amplitude [33].

A third approach becomes increasingly interesting for more complex grippers such as multi-fingered robot hands. It investigates the possibility of designing structures with orientation-dependent maximum forces. In the work by Grebenstein [33], for example, the fingers are connected to the palm through a joint that is specifically designed to dislocate, when experiencing lateral forces that exceed a certain limit, while withstanding greater forces in grasping direction. Besides the advantage of limiting the risk of damaging the expensive hardware in case of collision, occurring forces in case of lateral impacts can be adjusted to reduce the risk of injuries.

To enable a safe collaboration, the requirements of DIN 15066 are implemented in use case 2 (Sect. 3.3). On the one hand, this applies to the robot used from the company Franka Emika, which has integrated force torque sensors and thus stops moving in case of contact with the human worker. On the other hand, the robot tools used for handling and forming the textile materials are developed and designed in accordance with VDI standard 2221, with special regard to DIN 15066.

For example, handling tools are being developed which are made of carbon fiber reinforced plastic tubes and are therefore very lightweight. For both handling and forming tools, all edges are rounded and the contact area is maximized. Furthermore, soft materials, e.g., silicones, are used to ensure that humans cannot be harmed when working together with the robot.

To complete the safety concept, external camera systems are used, which can detect and predict human movements using CV (see Sect. 4.2). In this way, collisions can be largely avoided. During the implementation and regularly during usage of the collaborative workstation, the TOP model is being used which includes Technical, Organizational and Personal measures. In addition, a risk analysis is being performed so that all risks can be identified and eliminated at an early stage.

4.4 Human Acceptance and Trust

In addition to the soft- and hardware-based components presented in the previous sections, trust and acceptance are two important human factors for safe human-machine interaction:

In this context, trust is a multidimensional construct [34], for which there are many models [35]. Based on Hancock et al., Khavas et al. identify as trust-influencing factors those that are (1) robot-related, (2) human-related, and (3) task- and environment-related. As for the robot, a further distinction can be made between performance-related, behavior-related, and appearance-related. [36, 37] Distrust is expressed by the fact that users either do not use the machines or robots at all or intervene prematurely in processes because they believe that the machine cannot perform the task correctly [34]. Overtrust, on the other hand, may lead to a situation where the human, relying on the machine, does not intervene even though it would be necessary [35]. Both distrust and overtrust are subsumed under the term mistrust.

Acceptance is also a multidimensional construct and in the context of work primarily affects productivity. It is strongly influenced by trust [8, 36]. Furthermore, other factors - such as culture [37] - play a role. A connection with personality is also suspected [38]. Lack of acceptance may lead to a reluctance to use collaborative robots.

A study is currently being prepared on this topic. It will examine acceptance and trust in handling dangerous tools such as knives in a use case from textile production. The HRC will be evaluated depending on the speed of the dummy tool and its distance to the human as well as the possibility to influence the process.

5 Conclusion and Outlook

In this paper we provided an overview about currently researched concepts on safety for HRC within the cluster IoP. These range from the use and verification of BT the integration of CV algorithms, to a safe end-effector design and the consideration of human acceptance and trust. Furthermore, two use cases for HRC in the assembly process as well as production of FRP part were presented, classified using the extended framework developed by Baier et al. and validated regarding their compliance with current safety regulations [2]. Since the scope of this paper emphasized the context of the cluster IoP, we do not claim completeness, but are rather focused on transferability and interdisciplinarity.

For safe HRC, future robots embedded in an Internet of Production should be able to plan their task for highly dynamic environments. This should be done while not only maximizing the safety of the human coworker, but also the overall performance of the production tasks. Additionally, the robot should use the digital shadows of the processes, materials, and products to modify the behavior models designed by the human operator if needed.

Complex environments make it difficult to analyze the system, since it must be modeled as well. A possible solution would be to analyze the system during runtime. This approach makes the modelling of the environment unnecessary but would no longer verify the complete system. Regarding the CV algorithm, a GPU will be used to repeat the tests while detecting the whole human body as well.

For a safe collaboration, it is inevitable to not only use a safe robot, but also design safe robot tools with regard to the active and passive safety measures described in DIN 15066. Furthermore, the installation of external sensors (e.g., camera equipment) is inevitable to ensure safety.

Finally, the system should incorporate human digital shadows to model and take into account human behavior and human factors. For that, it is necessary to collect data from the human workers to predict their movements and fatigue as well as save their knowledge. This requires external sensors and intelligent software.

In conclusion, these developments pave the way for more flexibility and digitization in production through the use of HRC as part of the vision of the cluster IoP.

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