A new strategy for ensuring human safety during various levels of interaction with industrial robots

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ABSTRACT

The need for cooperation between humans and industrial robots is in exponential increase, especially in production applications. However, human safety is the main concern, preventing any fenceless cooperation between humans and industrial robots. This paper presents elements of new strategy for ensuring human safety during various levels of interaction with heavy-load industrial robots. The proposed approach classifies the human–robot interaction (HRI) into four levels. In every level, different kinds of safety functions are developed and analyzed. An additional algorithm has been developed for classifying the dangerous during the interaction. The proposed approach is tested and analyzed on a HRI platform.

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1. Introduction

Numerous scientists and researchers are eagerly looking forward to establish a real industrial application where humans and industrial robots can cooperate without barriers in a safe and efficient way. Various ISO standards have been published in recent years for paving the way to achieve this ambition. ISO 10218-1/2 [1] was published in 2011. It came with various safety requirements which make the industrial robot more fit for working with humans in a collaborative workspace. However, the procedures were very restricted. They eliminated any direct interaction between human and industrial robot. In 2016, ISO/TS 15066 [2] was published to supplement ISO 10218-1/2 and to provide additional guidance and more safety methods for human–robot interaction (HRI). In this ISO standard, four collaborative operations have been defined: (a) Safety-rated monitored stop: The robot is not allowed to enter the collaborative workspace as long as the human is inside this area. When the robot system is in the collaborative workspace and the human enters this area, the safety-rated monitored function will be activated and the robot motion will be stopped. (b) Hand guiding: In this operation mode, the human enters the collaborative workspace, then the system activates the safety-rated monitored stop. Now the human has the possibility to actuate a guiding device to activate the robot motion. The robot motion can also respond to the human commands. (c) Speed and separation monitoring: The robot speed directly correlates to the safe separation distance between the robot and the human. Whenever the distance is smaller, the robot should be slower. (d) Power and force limiting: The incidental contact, which is initiated by the robot, should be with limited impact to avoid any harm to the human. This also means that the robot design should eliminate any pinch points or sharp edges. Furthermore, the robot should be able to comply and react upon contact.

The safety requirements described in the current ISO standards rather provide guidance than clear standards. Furthermore, many issues are still ambiguous, e.g. how to define the required safety functions for various levels of interaction between human and robot? Which operational functions and methods should be applied on each level? Which human features (e.g. whole body, hand-gestures, face, readiness, etc.) are required and should be precisely detected? Which robot parameters should be measured or controlled during each level of interaction? Numerous other points need to be discussed and systematically classified to ensure safe and effective interaction between humans and industrial robots, which leads to new research approaches.

The next section briefly deals with the state of the art regarding the safety procedures in HRI. Section 3 presents some of the most required types of interaction between humans and robots in the industry and classifies them using a newly developed classification system of four levels. The recommended safety functions and the required features in every new interaction level will be illustrated in Section 4. Section 5 presents a newly developed HRI platform, including results of the various strategy-levels. Finally, the proposed approach will be discussed and concluded.

2. State of the art

Previous works [3,4] have categorized the HRI systems into “workspace sharing” and “time sharing”, depending on their function. In workspace sharing system, humans and robots perform separate tasks. In time sharing system, humans and robots perform one task together. Numerous papers have focused

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on human safety during the interaction with industrial robots. They have discussed the safety from different aspects. For instance, [5] has discussed the safe design of human robot workplaces, while in [6] an augmented reality system has been used for safer interaction between human and robot. [7] has integrated different types of sensors to ensure human safety during the interaction with industrial robots. Other papers such as [8,9] have developed special robot control strategies and safe controllers. [10] has even evaluated the injuries which could occur during the human–robot interaction related to robot speed, robot mass and constraints of the environment. Hidden Markov Model (HMM) has been used in an assembly task in [11]. They analyzed the process of joint assembly work, which was carried out by only one person in the presence of an assistant robot. In [12] a probabilistic approach was developed for ensuring the human safety in shared assembly tasks. [13,14] have proposed advanced vision algorithms based on depth images to ensure human safety. In general, most of the developed algorithms and the proposed safety functions have taken into account the safety procedures from one aspect for a specific task without taking into account the variance of the required shared tasks between human and robot. In contrast, this investigation has proposed a methodology for defining general safety functions which could be applied in different types of HRI.

3. Interaction-levels between human and industrial robot

The proposed approach has focused on the shared workspaces where the safety procedures are very stringent. It has taken into account some of the most required types of industrial tasks of humans and robots and their variance. Furthermore, a new classification strategy has been proposed depending on the level of interaction. According to this approach, most of the possible HRI in industry could be classified into four levels of interaction, as shown in Fig. 1.

3.1. Shared workspace without shared task

This level is defined when the human needs to work near the robot due to limited workspace or process flows. The human and robot each have their own task. However, the robot or the human should prepare the workspace components in an intermediate storage for their partner. Hence, they are acting in a shared fence-less workspace. This workspace can be virtually divided into two zones for human and robot. The human can move in his/her zone while the robot can move freely only in its zone at the maximum allowed speed. Once the human enters the robot zone, the system will register a danger status and the robot will be directly stopped. The human zone is a static one, while the robot zone could be configured either as dynamic (coupled with robot motion) or as a static one (limiting the robot to a specifically defined zone).

3.2. Shared workspace, shared task without physical interaction

In this level, the human and robot have a shared task, but the cooperation is very low. A third zone (see Fig. 1, level 2, zone 2) can be configured as a cooperation zone. There is no direct contact between human and robot. The robot can move toward the human only to a predefined position for assisting him/her as a third hand. It can hold a component firmly while the human is performing an assembly task. In the cooperation zone, the robot should decrease its speed according to the distance to the human.

3.3. Shared workspace, shared task “handing-over”

In this level the shared task consists of a direct handing-over between human and robot. Nevertheless, a physical interaction is completely excluded. A suitable example of level 3 is given, when the robot brings a required component/tool from the provision-line and hands it over directly to the human on the assembly line. Another possibility exists when the robot directly grasps the required components/tools from the human hand. Within the cooperation zone a special zone can be defined for handing-over. In this zone, hybrid control should be implemented. It allows the robot to react to the motion of the human hand and follow it in the free space.

3.4. Shared workspace, shared task with physical interaction

In this level, physical HRI is necessary to fulfill the task. For instance, the robot can bring heavy components to the human or to a predefined position near the assembly line, then the human can guide the robot to a final position by using human forces.

4. Proposed safety functions

Based on the four newly defined interaction levels, a taxonomic strategy was developed to classify the required safety functions and to define which human features should be detected and which robot parameters should be monitored or controlled, taking into account the ISO standards. This strategy aims to establish safe and active HRI, simultaneously using optimal capabilities of sensors and algorithms, starting from the first level of interaction and ending up with the most sophisticated physical interaction in level four.

Fig. 2 illustrates several proposed safety functions which may be required in each cooperation level. The safety procedures should be stringent according to the type of the cooperation between human and industrial robot. Whenever the human has a higher...
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