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An Automated Runtime Safety Supervision Approach for Multi Human-Robot Interactions

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Abstract—This paper presents an automated runtime supervision approach for human safety assurance in the context of multiple Human-Robots interactions. The system is capable of dynamically examining the risk associated with operations in Human-Robot collaborative workplaces, and mitigating the risk based on an adaptive safety strategy that ensures human-robot accident avoidance while reducing untimely interruptions of operations. The proposed supervision solution can be flexibly used in existing industrial factories as it is implemented independently of specific robot types and robot automation levels.

Index Terms—Human-Robot Interactions, runtime supervision, dynamic safety assessment

I. INTRODUCTION

Research on Human-Robot Interaction (HRI) has emerged from joint operations between humans and robotic systems in the same place. HRI allows humans to benefit from the assistance of the robot for performing arduous or repetitive tasks in factories. The use of robots helps reduce work hardship and boost worker productivity and can improve safety, e.g., by avoiding human exposition to radiation, noise, toxic fumes, excessive heat, etc. The close proximity of these robots to humans may represent a significant challenge to satisfy the applicable safety requirements for collaborative industrial robot systems according to ISO 10218 [1] and ISO/TS 15066 [2] standards. Indeed, in HRI, it becomes sometimes difficult to predict human and robot undesired behaviors that may cause situations at risk and lead to accidents. This is due to the various robot features (e.g. robot weight, range, speed, etc.) largely dependent on robot types, as well as possible human errors. Human safety is therefore becoming a key component in HRI.

In the literature, it exists different approaches to ensure safety in Human-Robot Collaboration (HRC) [3]. Some work trends consist in limiting the impact forces of robots to an acceptable level to avoid human damage. These work assumed that one develops safety mechanisms during the robot design, so they are hardly usable in existing workplaces, nor in workplaces where evolve robots from different manufacturers/providers. Other approaches rely on supervision solutions based on human attention - on-site via a remote monitoring solution - to monitor a large working environment and may require to designate several people for continuous monitoring. Such solutions can be constraining and expensive,

and fails at certain times depending on the cognitive charge of the human supervisors. For this reason, automated supervision approaches are to be preferred. Automated supervision [4] relies on sensors to monitor the HRI environment. It has algorithms to help identify and predict risky situations to issue alarms or stop the machines. It takes into account the real-time aspect as human safety must not suffer from any delay in detecting dangerous situations and in implementing measures to safeguard human integrity.

In this paper, we present an approach for ensuring human safety in a multi HRI environment, in light of safety and industrial requirements standards. We propose an automated supervision system capable of continuously monitoring humans and robots behavior, dynamically detecting and predicting dangerous situations, perform an online diagnosis of the situations to execute the adequate safety strategy to prevent the occurrence of an accident. The approach is robot-design independent, which enables bringing it into service in an existing and flexible industrial HRI workplace.

The rest of the paper is organized as follows. Section II presents our approach for runtime safety supervision of a multiple human-robot collaborative environment. In Section III, we illustrate the application of the approach in a case study involving multiple robots and a human in a shared working area, in a simulation tool. Section IV concludes the paper.

II. METHODOLOGY

Our approach for runtime safety supervision of HRI in collaborative workplaces follows two phases. First, we perform an offline risk assessment to identify the causal chains of events and associated criticality levels that may lead to accidents or undesirable behaviors in the working environment. The analysis is formalized as a finite-state automaton, as presented in Figure 3. We also define a mitigation strategy to trigger control actions aiming at avoiding accidents according to safety metrics and thresholds defined in the automaton. Both the safety automation and the mitigation strategy form the core module of the supervision approach, as discussed in Section II-A.

At operational time, the preceding safety module is exploited to implement the concepts of *situational awareness* and *adaptive safety*, as explained in Section II-B.

Process	Hazard	Effects	Causes	Current process controls	(DPH, PO, FE, PA, PHR)
Objects Pick and place by robotic arm	Unexpected robot startup	Collision, Shearing, Crushing	Robot automatic ignition after power cut recovery	Controlled stop	(25, 2.5, 5, 1, 312.5)
	Falling or ejection of robot's part	Collision, crushing	Articulation loosening, mechanical hazard	Articulation joint control, speed limitation	(3, 2.5, 1, 2.5, 18.75)
Assembly of the finished product by human	Human maladaptive movement	Collision, Crushing	Health problems, human errors	-	(5, 2.5, 3, 5, 187.5)
	Momentary loss of visual contact of the working area	Crushing, Perforation	Fatigue, human inattention	Periodic rest	(0.75, 6, 3, 2.5, 33.75)

TABLE I: Excerpt of Risk Analysis results in an FMEA format. Risk estimation factors are defined from Pilz Hazard Rating scales from negligible (in green), low (in yellow), significant (in orange) to high risk (in red);

A. Risk analysis and mitigation strategy.

To prevent accidents in an HRI workspace, it is necessary to identify the potential sources of accidents and to evaluate the damage they may cause. We perform a risk analysis based on a FMECA-like method (Failure Mode, Effects and Criticality Analysis) [5] to gather these information. FMECA is a systematic risk analysis method to determine the failure modes of an item or process, and attribute them a criticality level. The analysis results are usually presented in a tabular form with the failure modes, their causes, effects, detection controls means and criticality level. Table I presents an excerpt of a risk analysis with four identified failure modes on different process activities. Note that the failure modes identification can be completed with a review of existing accident databases and an analysis of safety standards.

For the criticality level determination, we estimate the risk based on the Pilz Hazard Rating (PHR) formula 1:

$$PHR = DPH * PO * FE * PA \quad (1)$$

With the factors DPH as the severity of the potential harm, PO as the probability of occurrence of the hazardous event, FE as the exposure of people to the hazard, PA as the possibility of avoiding or limiting the harm, as defined in ISO12100 standard [6] (see Column 6 of Table I). The PHR helps us classify the risk incurred by a human in a workstation with direct collaboration with a robot from negligible to very high risk to better identify those on which actions must be taken as a priority. We formalize the risk analysis results as a hierarchical automaton where a state represents the set of situations corresponding to a risk class and the transitions define the conditions and events that let move from one risk class to another.

Risk reduction measures must be recommended according to the assessed risk to increase safety and reduce accidents. There are two categories of measures: preventive control actions to avoid damage and corrective control actions to limit damage. Those control actions depend also on the mode of operation of the machinery, e.g. remotely controlled, semi-automatic, or fully autonomous. In our approach, we choose to develop a three-layer control actions strategy. The first layer is about detecting the surrounding entities and inform about their position. The second layer helps track detected entities and

sends an audible or visible warning in case of near hazardous situations to alert the person exposed to the danger. The third layer is configurable to either permit immediate actions on the machines or provide assisting information to avoid accidents.

B. Runtime safety assessment.

Our runtime safety assessment is based on sensors that monitor the HRI environment. Data collected from the sensors are processed to identify reliable positioning/detection of the surrounding entities in the supervised workplace, together with additional characteristics such as their speed, orientation, relative distance, etc.

We develop a safety function that uses information from both the active sensing and tracking of humans and machines, and the automaton resulting from the prior risk analysis as a dynamic model to predict the potential hazardous situations in real-time. We use an event-driven algorithm to evaluate automatically the risk level incurred for the human in operation from the observed events and the states encoded in the automaton and launch accordingly the appropriate risk reduction measures. Evaluating the hierarchical automaton consists in determining the transition to be fired from an active state or current state S . In the generic principle [7], a transition is automatically fired from a state S as soon as its triggering event is observed, and its guard is satisfied. If a transition is fired, a risk level is calculated and the target state of the transition becomes therefore the current state. If none of the transition from S is fired then, one is recursively interested in the transition of its immediate upper hierarchical state. Whenever a current situation is identified as corresponding to an automaton state S , appropriate actions are launched according to the defined control action for this state.

III. ILLUSTRATIVE CASE STUDY

We use a representative use case to demonstrate our approach for HRI runtime safety monitoring.

A. Case description

The use case concerns the cooperative work on an assembly line between a human operator, a robotic arm, and a mobile robot, as shown in Figure 1. The robotic arm manipulates and moves parts to make them available to a human operator. The operator assembles the parts as a finished product. He



Fig. 1: A representation of Human Multi-robots collaborative work on an assembly line.

places the assembled product on a conveyor belt that transits it to a mobile robot. The latter robot moves the product to a shipping area. For the supervision approach illustration, we work around the hazardous scenario consisting of an uncontrolled movement of a robot or the human that leads to a collision. The scenario applies to the human, the mobile robot and the robotic arm, thus allowing a more complete evaluation of the approach.

B. Experimentation setup

We implement the automated HRI supervision approach in the CoppeliaSim simulation tool using ROS¹ and LUA, the default programming language of the simulator. CoppeliaSim was chosen because it allows to simulate both robot and human movements [8].

We also implement in the simulator our supervision approach which comprises the following elements:

- A camera-based perception module that collects successive images of the environment. An algorithm analyzes the images to detect different regions based on brightness or color. Then, one can recover the entities in the environment with their positions, represented by different colors that differ from the surrounding regions;
- A safety module that includes the automaton characterizing the possible dangerous situations with their associated risk thresholds and defined risk reduction actions;
- A diagnosis module that exploits the data treatment and the safety automaton for situation awareness. It enables to detect the occurrence of a situation at risk in real-time and launches the appropriate risk reduction action accordingly to the quantified level of risk;
- A graphical interface that prints the diagnosis information along the simulation run.
- In addition, a "log" module stores the history of all observed events and the corresponding quantified risk level, making it possible to carry out an offline analysis for future improvement of the supervision system.

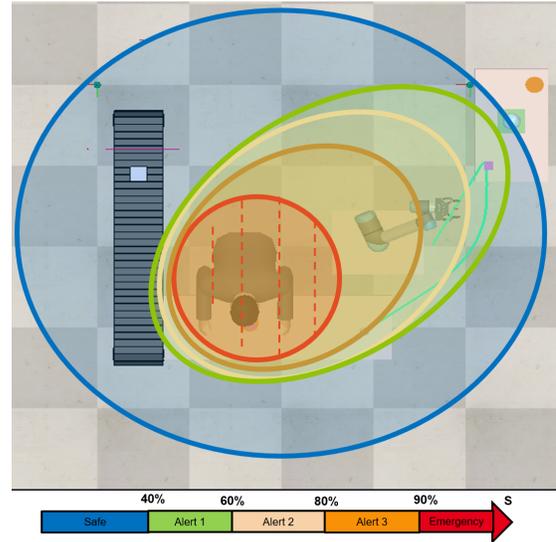


Fig. 2: Characterization of danger zones in the supervision system. The danger zone from the least critical (in blue) to the most critical one (in red) indicates the risk of accident between an human operator and a robot.

The architecture of the supervision system is modular and flexible so that one can supervise several humans and robots at a time; as well one can configure the safety module with different risk thresholds and risk reduction strategies per robot.

C. Results

Risk analysis and mitigation strategy. We follow the risk analysis method presented in Section II on our use case study to identify hazardous events, classify them (see Figure I), and build the automaton. One can trigger the transition between classes of risk based on different metrics, e.g. a motion-related metric, an interaction zone metric, a hazard type, etc., or a combination of them. For our scenario, we take into account only a distance factor as a metric. According to ISO 13855 standard [9], the minimum distance S between a robot and a human is defined by the equation:

$$S = (K * (T1 + T2)) + C \quad (2)$$

with K the approach speed of the body of 1600 mm/s; $T1$ the time between the detection of the danger and the emission of a stop signal; $T2$ the time between the reception of a stop signal and the stopping of the machine; and C the intrusion distance - which can be traveled by a body part towards the dangerous zone - of 600 mm.

We define our automaton with three main hierarchical states containing each internal compound states. The states represent the different levels of vigilance and alert that one must have according to the minimum distance allowed between the human and the robot. Figure 2 shows the characterization of the different states applied to the robotic arm as partitions around the human vital zone - which can be mobile too. The most critical state is the *Emergency* state which is composed of the *Critical Emergency* and *Fearful Situation* sub-states (see Figure 3). We are in a *Critical Emergency* state if the robot enters the human's vital zone. We are in the *Fearful Situation*

¹<https://www.ros.org/>

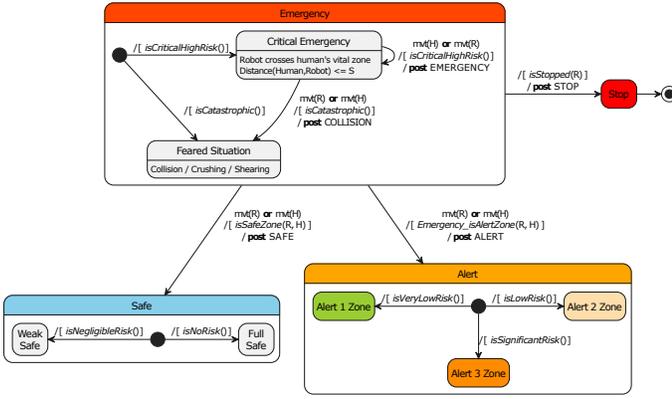


Fig. 3: Simplified automaton for risk level determination. A state formalizes a risk level and the transitions define the conditions of state changing.

state if the robot and the human collide. The upper hierarchical state is the *Alert* state which is composed of three sub-states: *Alert 1 Zone*, *Alert 2 Zone*, and *Alert 3 Zone*. The outermost state is the *Safe* state, composed of two sub-states *Full Safe* and *Weak Safe*. One is in the *Full Safe* state if the robot is stationary, and in the *Weak Safe* state if the robot is moving. For our use case, we arbitrarily define the scale of the alert thresholds at 40%, 60%, and 90% of the relative distance between the robot and the human (see Figure 2).

The modular design of the supervision system allowed us to instantiate the automaton twice, one per robot since they present different risk thresholds (due to different speed, position, etc.). For risk reduction, we choose as measure the emission of audible and visible warning signals. An election system was implemented to prioritize the alerts depending on the highest calculated risk from the two automatons. Different sounds are issued depending on the threshold crossed by a robot. A console displays the current state and the entity at the origin of the notification as the visual warning.

Runtime safety assessment. Events are continuously produced by the sensors during the simulation. They are collected periodically, every 5 simulation time steps. This sampling period “*t*” is experimentally determined taking into account the event computation time and to avoid delay in the simulation rendering. A “*motion*” event is created when the position of an entity changes during this time interval. The created events are filtered to keep only the relevant ones with regard to the risk analysis, i.e. only events that may trigger an automaton transition, depending on the relative distance between the robot and the human.

The observed events from the modeled hazardous scenario are checked against those pre-encoded in the automaton to deduce the current risk level using our event-driven algorithm. Concretely, according to the simplified automaton presented in Figure 3, if the current state $S = \text{Critical Emergency}$, then two outgoing transitions may be fired when a human or a robot movement occurs. Then, one must define the next target state by evaluating their guard depending on the estimated current risk level, namely :

- `isCriticalHighRisk()` is evaluated to True if the movement of the observed entity resulted in a movement of the entity towards the vital area of the human and the current state remains the same. The alert signal “STRONG EMERGENCY” is printed in the console.
- `isCatastrophic()` is evaluated to True if the movement of the observed entity has caused a collision between the robot and the human and Feared Situation becomes the current state. The alert signal “COLLISION” is printed in the console.

Note that if none of the two guards are satisfied, then the target state is one of the compound states of an upper hierarchical state between *Safe* or *Alert*. The new current state will be chosen according to the satisfaction of the guard of the transitions from the initial state of this hierarchical state. For example, if the guard `isSafeZone(R, H)` is evaluated at True, then the guard `IsNegligibleRisk()` or `IsNoRisk()` must be also evaluated to reach the new current State.

IV. CONCLUSION

This paper presents an automated approach for runtime supervision of human safety in human-robot interaction workplaces. The approach relies on a perception system to gather information about the entities present in the supervised workspace, a risk analysis module that enables the definition of undesirable incidents and assessment of their inherent risk, a decision module responsible for real-time prediction, detection of dangerous situations, and triggering appropriate alarms according to the observed risky situations to ensure human safety. The mitigation strategy can be adapted to be more and less active depending on the robot automation levels. We illustrate the application of the approach on a use case within the *coppelasim* simulation tool. The use case elaborates on the collaborative work between a human, a mobile robot, and a robotic arm on a production line. Compared to safe-by-design HRI approaches, our approach is developed independently of any robot type. It is enough modular to be configured for supervising several humans and robots at a time. Overall, we provide industrial end users with an easy-to-integrate automated supervision approach that can be flexibly used in existing human-robot collaborative assembly lines to enable a safer collaboration. It will also help increase logistic efficiency by reducing the cognitive charge of human supervisors to supervise a large area, and it will reduce the cost resulting from the untimely stops of the machines based on the adaptable mitigation strategy.

Currently, our approach addresses safety-related concerns. In future work, we are interested in developing the supervision approach with other types of sensors (temperature, noise, etc.) to also address privacy requirements with regard to GDPR (General Data Protection Regulation). Furthermore, we would like to develop the risk analysis to address complex sources of human hazards, e.g. loss of human consciousness, fatigue, that are hard to capture through perception systems only.

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