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Safety of Interactive Robotics—Learning from Accidents

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Abstract Finland is ranked rather high in international robot density statistics. In Finland, robots are typically used in applications where they operate in close proximity to humans. The research described in this paper, sourced from Finnish databases, identified 25 severe accidents which can be attributed to robots. The current accident data can provide an insight into the type of accidents associated with future human-robot interaction (HRI) applications. Accident statistics indicate that most of the severe robot-related accidents involved crushing a person against a rigid object. As crushing hazards currently dominate accident statistics, and with HRI applications becoming increasingly common, humans are expected to be exposed to more crushing hazards in the future. The close proximity of the robots means that there is very little time to escape from crushing hazard. The prevention of collisions between robots and humans is paramount to reducing the amount of accidents. Actions to diminish the effects of any subsequent collision are also important. The control after a collision, however, needs to be very quick in order to minimise the damage caused by an impact. Current practice demands that upon detection of a collision, active movements are typically not allowed without a human supervision. Moving a robot away to a safe position and releasing any pressure against a person may save lives, but would entail some adjustments or new interpretations of the current safety requirements.

Keywords Robot · Accident · Safety · Hazard · Crushing

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1 Introduction

Placing about seventh place in robot density in the world, Finland is ranked rather high in international robot density statistics. In Finnish industry, humans and robots are typically working in close proximity. Because there are not many completely robotised automated production systems in Finland and a large amount of people are typically working in close proximity to the robots, the cases in the Finnish accident study resemble more the situation of collaborative robotics where there is a degree of human-robot interaction (HRI).

The findings from the Finnish accident studies help provide an insight into the kinds of accidents that are associated with an increasing amount of HRI based applications. The findings can also help designers to choose safety functions for simple and also sophisticated human-robot interactions. As the principles of safety apply equally to different technological appliances, many safety principles of industrial robots can be applied also with social and service robots.

This paper presents (a) safety issues in industrial robotics and the synergy with other types of robotics, (b) typical usages of robots and descriptions of HRI in Finland, (c) observations associated with an analysis of robot-related accidents in Finland. Section 2, *Related work*, presents studies, which support the findings in this study. It also presents a basic overview of robot related safety requirements, and requirements related to collision and crushing (which are at the root of the most severe robot accidents). Section 3, *Data*, and Sect. 4, *Analysis*, present the accident study that was performed. Section 5, *Discussion*, describes major observations and provides some ideas on how to diminish the hazard of collision.

2 Related Work: Human-Robot Interaction and Risk Studies

International accident-report data related to robots is scarce. However, some research has been done over the past few years [3, 12]. One reason for the minimal amount of accident data is that this data is hard to distinguish from general industrial accident statistics [6, 12].

According to Karwowski's report, in most of the reported lethal robot accidents the robot forced and clamped or crushed a person against a stationary object [12]. According to tests run by Haddadin et al. [8] it is unlikely (but possible) for a robot to strike a person lethally in an open space. The danger becomes substantial, even at low speeds, if a person is crushed against a rigid object. The studies are based among others on practical tests using crush test dummies. The head acceleration and HIC value (Head injury criteria) are compared with car crushing tests (EuroNCAP), and impacts with sharp objects are not included, since the danger is obvious and difficult to measure. Impacts which don't involve clamping can nevertheless lead to less serious injuries such as bone fractures [7–9].

Kuivanen presents some problems related to accident reporting. One report about a minor robot-related injury described how a worker contracted a sore elbow because the robot was broken—while, in fact, the injury to the worker arose because the worker had to carry beverage barrels by himself, as the robot was not operational [14]. Analysis of reported statistics of especially minor accidents can thus be problematic. Kuivanen considers also the risks related to working with robots, and claims that the risks should be compared with the risks of normal everyday life (a type of voluntary risk). While it can be argued that accidents are never acceptable, the risk level can still be considered to be "acceptable" [14].

Along with identifying and considering the possible human entries to the robot operating area, the safety planning should also take into account the variations in human performance. Irrespective of the cause of the entry, the possible human actions can be hard to predict and consider in robot and safety system design. Thus, all the technical systems around and within the robot operating area should be inherently safe (see Kletz [13]). The expected and planned operations should be identified and planned in such a way that the system is resilient to variations in human performance. In this case, resiliency conveys the idea that the robot and the safety systems are tolerant to any misuse and minor faults that the human may cause while operating or maintaining them (see Hollnagel et al. [10]). Designing and applying resilient technologies should also promote the safety of the unexpected and unwanted situations.

There are requirements for industrial robots mostly within ISO 10218-1 (Robots for industrial environments—Safety requirements) [4] and in the future Part 2 (Robot system and integration) [11]. Currently, no international standards specifically address HRI and therefore developers need to apply industrial robot standards. The draft ISO 10218-2 defines a collaborative workspace as a "workspace within the safeguarded space of the robot work cell, where the robot and a human can perform tasks simultaneously during production operation". Also the safety principles for collaboration are defined. However, if someone develops a safety measure which is as safe as stated in a harmonised standard, it can be accepted according to the procedure of the European Machinery Directive (2006/42/EC). Since the definitions and principles are new, they may still change and be refined.

One particular requirement, however, may need a new interpretation in the future. Basically, according to ISO 10218-1 a robot must stop in the event of a collision. Collisions can be either be deduced or detected with external sensors; at least a collision typically results in a detectable malfunction since the robot cannot reach the intended target at the expected time. In both cases this would result in a protective stop, which resembles emergency stopping, i.e. category 0 or 1 stopping according to EN 60204-1 [5], and no movements would be allowed… unless a risk assessment permits otherwise [4, 11]. Movement "backwards" means that the robot should actively move in a specified direction. While such movement would be contra to the requirement, the risk assessment may present a "back door".

3 Data: Methods and Materials

3.1 Robot Systems Under Examination

In Finland, there are a total of about 6000 robots and in Finnish industry there is approximately 1 robot per 100 employees in the industry. This is especially interesting considering the nearly non-existent automotive industry in Finland. A substantial amount of the robots in Finland are used for handling operations and machine tending, i.e. about

28% of all robot installations. Other common robot applications include arc welding (approx. 18%) and assembly (approx. 17%) [15, 17, 18].

The majority of the 6000 industrial robots in Finland are used in small robot work cells rather than in large automation lines. The characteristics of the Finnish manufacturing industry are: (a) large and heavy products, (b) small lot sizes, and (c) short production runs. A natural feature of the production is that it requires substantial (mainly simple) HRI, also inside the robot working envelope. Moreover, due to heavy and large parts, the automatic material handling is usually awkward and unreliable, and robot production cells are therefore usually loaded and unloaded manually. Because of the very common small lot size, other typical tasks inside the robot working area are associated with teaching activities.

The food and beverage industry makes use of approximately one tenth of the total robot installations in Finland. Robots, in these cases, are typically installed into enclosed spaces which are fenced off and access is tightly controlled. Most common robot applications in these cases involve packing and palletising in highly automated mass production lines.

A systematic approach is needed for collaboration planning of robots and humans in a production environment, so that both have reasonably allocated and well-balanced tasks. Especially important is a careful requirement specification process, and a thoughtful system design process that meets the different user and robot system needs. If the utilisation rate of a user or a robot, or both, is not adequate (e.g. because of the flaws in system usability, or undefined tasks' allocation) both the production may become inefficient, and the user work may become unsatisfactory, which may give rise to various safety issues, human errors, and moreover economic inefficiency.

When a robot cell is planned to operate automatically without manual feeding, removal or troubleshooting, there is typically no need for a human to go inside a robot cell in normal conditions, and therefore there should not be any accidents. However, unplanned repairs, fine-tuning the process or the robot, and maintenance operations may require that a human enters the robot workspace. Moreover, since in the future there will be more diverse applications for various robots, there will be more tasks where the human and a robot need to function in close proximity and this is a challenge for safety engineers.

3.2 Databases

The study involved severe accidents, which caused long absences from the work. Severe accidents are fortunately relatively rare and in order to obtain sufficient research data, also relatively old accidents were considered.

In Finland the public, official accident databases cover all severe and fatal accidents relatively well, since an accident report is required in order to receive insurance compensation for the company and the victim. However, identifying the relevant accidents from the databases using specific words in the reports, does not guarantee that all relevant accidents are found. Noteworthy is that the investigators writing the accident reports do not necessarily have the same opinion about robot definition and a machine can be called a robot even though it actually isn't, and vice versa. Furthermore, due to various reasons, in some instances also due to a lack of eyewitnesses, there can be variations in the interpretations on what happened and the actual chain of events which led to the accident. Also the availability of the case-specific details and the author-based variations in reports can vary greatly between the cases.

The Finnish Ministry of Social Affairs and Health hosts a database of severe accidents [2]. The accident investigations are coordinated by the industrial safety districts, and the reports are therefore composed by the local industrial safety authorities. One or two safety inspectors from the associated local safety district would investigate and report the severe accidents. The database of severe accidents includes also workplace fatalities, although their detailed investigation and reporting is centralised to the Federation of Accident Insurance Institutions in Finland (FAII). After a fatal accident, the FAII forms an expert group based on the accident case and industry. The final reports are public and delivered to the companies operating in the same industrial sector. The reports typically include 4–6 pages of text describing relevant background information and the chain of events chronologically. Various photographs and a sequential model of the accident chain are normally also incorporated.

This study included both severe non-fatal accidents and fatalities, as reported in the databases. The relevant available cases from the period 1987–2006 were investigated, and the first robot-related accident was in 1989. All the accident descriptions that had either the term "robot" or "manipulator"

Table 1 Robot-related severe accident from the Accident Report Database (TAPS) of the Safety Administration in Finland

Year	Quantity	Year	Quantity
1989	2	1998	0
1990	1	1999	1
1991	0	2000	2
1992	0	2001	2
1993	0	2002	4
1994	1	2003	1
1995	1	2004	2
1996	0	2005	5
1997	1	2006	2

(in Finnish) were initially gathered. Occupational diseases and cases which were not related directly with robots were removed on a case by case basis. In some cases the accident occurred in another machine; the robot just happened to be beside the machine under investigation. In all the accepted cases the robot was either moving or it was being repaired. A total of 25 severe robot-related accidents were documented in Finland during 1989 to 2006 (Table 1), and a total of 8988 accidents have been reported to TAPS.

4 Analysis: Results and Discussions

The TAPS database reports that 25 severe robot or manipulator-related accidents occurred during the period 1989–2006, with 3 of those being fatalities. The accidents took place nearer the end of the period under review (i.e. during 2000, 2005 and 2006). Short descriptions of the events follow:

- 2000: The head of the victim was crushed between a conveyor and a robot. The task of the robot was to feed cows at a farm.
- 2005: The victim was crushed between a manipulator (resembles gantry type robot) and a conveyor. The task of the manipulator was to set bricks from one conveyor to another at a brick factory.
- 2006: The victim was crushed between a robot and a conveyor. The task of the robot was to set trays to a conveyor in the dairy industry.

The categorisation of the severe robot-related accidents was based on the operation tasks and causes of the accidents. Table 2 portrays troubleshooting as the most common operating mode for severe robot-related accidents and approximately half (48%) of the accidents can be categorised to this class. Also the amount of the accidents that occurred during production, and while an operator was programming or making settings and adjustments, were significant. One fifth (20%) of all the accidents took place during production (without any failures), and almost one quarter (24%) of the accidents occurred while the operator was adjusting different kinds of settings. Only one of the 25 severe robot-related accidents was deemed to be related to the tasks made by maintenance personnel (maintenance and repairing). In addition, the operation task in one of the lethal accident cases remained undefined.

4.1 Accidents and Operation Modes

Troubleshooting typically results in more severe accidents and the milder accidents occurred more during normal production [15, 16]. The statistics may, however, be somewhat distorted because of the relatively short descriptions of the accidents in the TAPS and FAII databases. In many cases (33%), the actual operation task could not be determined from the accident report.

Table 2 presents the severe robot-related accident causes. The fact that each accident had several causes means the total amount of the causes is significantly higher than the amount of the accidents.

Inadequate safeguarding was related to almost 80% of the accidents. Also the insufficient amount (or even lack) of warnings and/or instructions represented a significant role as a cause of the accidents (60%). These aspects, together with insufficient introductory briefings or supervision meant it was common to have dangerous working methods in use

Table 2 Quantity of severe robot-related accidents in different operating modes classified according to the cause or causes of the accident

	Total	Quantity in different operating modes				
		Trouble-shooting	Repairing and maintenance	Production	Setting, programming, adjustments, cleaning, tool change	Undefined task
Total (number of accidents)	25	12	1	5	6	1
Total (%)	100%	48%	4%	20%	24%	4%
Unexpected start-up	9	5	0	2	2	0
Mishap	5	3	1	0	1	0
Dangerous working method	11	6	0	1	4	0
Inadequate safeguarding	19	8	1	4	5	1
Inadequate design	9	1	1	1	5	1
Insufficient work experience	6	3	1	2	0	0
Failure	1	1	0	0	0	0
Poor visibility	0	0	0	0	0	0
Insufficient warnings/instructions	15	8	1	3	2	1
Haste	3	2	0	0	1	0

Table 3 Severe robot-related accidents from the Accident Report Database (TAPS) of the Safety Administration in Finland classified according to their causes or consequences

	Amount	% of all the accidents
Robot movement or operation	23	92%
Handling of objects and tools	1	4%
Moving, slipping, distortions	1	4%

(44%). The use of dangerous working methods were typical, especially when conducting troubleshooting (50%) and adjustments, etc. (approx. 67%).

4.2 Causes and Consequences

Additional analysis of the data provides the results as presented in Table 3. Almost all of the severe accidents were related to robot movements or operation. Furthermore, one of the severe robot-related accidents has been construed to be caused by handling of the objects or tools, and one accident was the result of a person slipping.

The share of accidents caused by robot movements is significantly bigger for severe or lethal accidents when compared to a previous accident study that dealt with all (minor) robot accidents in Finland [15, 16].

A significant number of accidents (64%) resulted in a variety of hand injuries. The most typical injury involved losing one or more fingertips due to crushing or cutting. One of the crushing accidents (finger damage) was the result of entanglement. The amount of corresponding damages for feet or toes was 12%. The remainder of the accidents were related to crushing of the body or head. All of the fatal injuries were the result of crushing.

Only 2 of 25 severe robot-related accidents were due to reasons other than crushing (against rigid object): one case involved falling/slipping, and in the other the robot collided with a ladder and the operator fell down.

5 Discussion: Main Accident Study Observations

In practice, accidents are especially associated with supportive tasks such as setting and adjusting. Many of the accidents occurred when placing or otherwise handling the work piece that the robot is processing.

A surprisingly large amount of robot-related accidents occurred in the food and beverage industry. The use of robots and automatic lines is very common in food factories, which significantly influences the statistics.

In the three fatal accidents that were reviewed, the victim was crushed between a conveyor and robot/manipulator. Moreover, 23 of all 25 severe injuries were caused by crushing. This clearly shows that special attention must be paid to the locations where a crushing possibility exists.

Robot-related accidents have only been extracted from databases using accident description keywords, because no other suitable categorisation exists. Descriptions from the TAPS database are relatively detailed, but due to the low number of reported cases statistical analysis would not be prudent.

Proper safeguarding would have prevented many of the studied accidents, however, normal high-quality safeguarding works efficiently only during production and troubleshooting. During programming, setting, and maintenance the worker may need to get close to the robot, and perhaps even into its working area. Usually, the fences and light barriers are not designed to protect a person working inside a robot cell while the robot is moving, and therefore are not suitable for any kind of HRI application.

5.1 Accident Characteristics

Analysis of the robot accident descriptions highlighted a set of traits. The following aspects were seen to be valid in almost all kinds of robot applications:

- The cause of an accident is usually a sequence of events, which have been difficult to foresee.
- Operator inattentiveness and forgetfulness may lead them to misjudge a situation and even a normal robot movement may surprise them.
- Most of the accidents involving robots occurred so that robot moved unexpectedly (from worker's point of view) against the worker within the robot working area.
- Inadequate safeguarding featured significantly as a cause of accidents.
- Many accidents are associated with troubleshooting disturbances.
- Only about 20% of accidents occurred during undisturbed automated runs.
- Almost all of the severe accidents were as a result of crushing between the robot and a rigid object.

5.2 Safety Measures for Hazards Prevention

In order to prevent the large proportion of accidents involving crushing between a robot and a rigid object, specific attention should be paid to crushing hazards in risk assessments. The risk assessments concerning robot systems should also take into account intentional, unintentional and accidental entry into the robot workspace. The results from the risk analyses should be considered carefully in any subsequent robot and safety system design, as well as in task planning.

It would be best to use safety devices in order to avoid collisions between a human being and a robot. The accident data indicates that most of the accidents occurred during special situations when a person needed to perform a task alongside a robot. The use of current safety measures can be challenging when a person and a robot are in close proximity, e.g. in HRI applications. Therefore another additional strategy might be required in order to diminish the severity of any collision.

5.3 Safety Measures for Diminishing Consequences

An impact hazard is very quick and the system should operate very quickly (i.e. some milliseconds) in order to minimise the hazard after the collision. The crushing hazard does not necessarily demand as quick reaction after collision. In 2 out of the 3 lethal robot accidents in Finland, the human body was in a crushing situation for a considerable period and a pressure release could have saved the persons. In all of the fatal accidents the victim was working alone. If a colleague had been present at the time of the accident, the consequences could have been milder.

A quick stop after a collision typically means a crushing situation continues, since the brakes keep the robot in the crash position. While it might be possible to ensure the brakes are released, this may mean that the robot arm falls down, and presents an additional hazard (although the speed can be limited). It may be safe to release the brake of the first joint, but even this doesn't always sufficiently minimise the risk.

Software options for collision detection exist in some robot controllers. Such systems can detect abnormal forces directed at the robot end effector, for instance, in a crushing situation. These systems are, however, not specifically portrayed as safety features, but they have features that can lessen the damage caused by crushing. When such a systems is activated, the robot would move backwards along the trajectory it was moving before the crushing situation arose. This is the safest direction that can be considered in a generic case. The robot will automatically stop its "backward" movement when a preset distance has been travelled or the overload situation ends.

One concern with such movement is that this would involve automated active movement after a protective stop situation. Who takes the responsibility in such a situation? According to ISO 10218-1 the robot should stop in a protective stop situation and someone should take responsibility for this additional "illegal" action, which might save someone's life. A risk assessment may show that backwards movement is safe and justifiable. However, it is possible that in some rare cases (e.g. a person puts his hand into a corner immediately after the collision or the robot has a failure of a position sensor at the same time as the collision) any subsequent active "safe" movement could have hazardous results. While the user could set the robot parameters to allow the safe movement, it would raise both legal and ethical questions. Some adjustments or new interpretations to current regulations may be needed to justify safe movements after a collision.

An alarm that is triggered by a collision detection fault signal could also be set up. The robot's backward movement could then be activated manually using a separate safety button which, for example, is pressed by a colleague. When this path recovery function is activated on the controller, the robot would move backwards along its trajectory prior to the accident. Naturally this feature will improve safety only in the cases when employees are not working alone [1].

6 Conclusions

While Finland is ranked rather high in international robot density statistics, and robots typically operate in close proximity to humans, severe accidents involving robots capable of sophisticated human-robot interaction (HRI) have yet to be observed. This may be due to the relatively low direct collaboration and HRI in Finnish industry.

A robot-related accident study indicated that specific hazardous traits related to 25 severe accidents attributed to robots include: crushing hazard, unexpected start-up, and dangerous working method. Working alone has also been an important factor in reported lethal accidents. These risks are especially relevant in cases where a person is working alongside a robot, for example, in HRI applications. Many other risks exist, and would need to be considered on a case by case basis.

Crushing currently poses a major hazard in robot cells, and with HRI applications becoming increasingly common, humans are expected to be exposed to more crushing and clamping hazards in the future. To best avoid severe accidents, collisions between robots and persons should obviously be prevented, and especially in cases where a person cannot escape from being clamped. Inadequate safeguarding was highlighted as a significant factor in the reported accidents. Nevertheless, actions to diminish the effects of any subsequent collision are also important. Robot control after a collision, however, needs to be very quick in order to minimise the risk related to an impact. If a quick response to a collision is technically not possible, a slower response with backwards movement can still diminish a risk of being clamped and suffocated.

Current practice demands that upon detection of a collision, active movements are typically not allowed without a human supervision. Although it is usually safe to move the robot "backwards" to a safe position after a collision is detected (in order to release any pressure against a person), such actions would entail some adjustments or new interpretations of the current safety requirements. Any amendments would need to be clearly communicated to the robot manufacturers who would then have more confidence in their proposed solutions.

A more effective approach would be to systematically identify solutions which diminish or hinder accidental access to the robot's working space by applying suitable safeguarding measures. Work procedures should be investigated and amended to eliminate any dangerous working methods. And situations concerning unexpected start-ups should also be examined. The solutions would then need to be considered for the different usage and maintenance situations. Because of difficulties in distinguishing the human movements and the material flow in a reliable way, a single measure is typically not adequate. A thorough risk assessment would be needed to show that all major risks have been addressed.

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