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SAFETY PRECAUTION FOR ROBOT-HUMAN INTERACTION

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ABSTRACT

Safety is an important consideration in humanrobot interactions (HRI). Robots can perform powerful movements that can cause hazards to humans surrounding them. To prevent accidents, it is important to identify sources of potential harm, to determine which of the persons in the robot's vicinity may be in greatest peril and to assess the type of injuries the robot may cause to this person. This survey starts with a review of the safety issues in industrial settings, where robots manipulate dangerous tools and move with extreme rapidity and force. We then move to covering issues related to the growing numbers of autonomous mobile robots that operate in crowded (human-inhabited) environments. We discuss the potential benefits of fully autonomous cars on safety on roads and for pedestrians. Lastly, we cover safety issues related to assistive robots.

INTRODUCTION

Robots can produce powerful and very rapid movements through a large operational space. Hazard threats arise from unintended contact between these robots and humans. The forthcoming paths of robots or robots' arms are difficult to predict (e.g., due to changing operational requirements). Operators can be required to work in close proximity to the robot system, while the machine actuators are being powered. Furthermore, the operating spaces of two or more robots can overlap, representing a threat to a human worker from multiple sources. Nowadays, humans work in close cooperation with robots more than ever. In the resulting situations, contact is unavoidable between humans and robots. Indeed, in many instances, it is actually desired. However, every contact creates the potential for an accident. Careful thought needs to be given to hazard assessment.

Once the hazards are known, they can be eliminated or reduced by design, safeguarding, control and other methods. Industrial robot interactions between humans and robots are perhaps the most well-studied in current literature. However, the emerging field of mobile and autonomous robots brings new threats that have not yet been equally well-assessed. When it comes to human safety, accident prevention can always be improved. There have been many accidents caused by HRI in the past. In the years to come, the number of robots surrounding humans will greatly increase. Hence, the potential danger from robots is greater than ever. The purpose of this survey is to review possible hazards and overview the methods used for accident risk reduction, as well as point outthe risks that did not exist before, but are being introduced with the development of modern robotic systems. II.

HAZARDS OVERVIEW

In order to improve safety in HRI, one needs to determine

- where the biggest danger lies,
- who is the most endangered person in the interaction with a robot,
- what are the consequences of potential injuries, and
- which factors have the greatest impact on safety?

In this section we address each of these questions in turn. A. Sources of injuries According to [1], the causes of accidents caused by robots can be grouped into three main categories: engineering errors, human mistakes and poor environmental conditions. Engineering errors include errors in the robot's mechanics (loose connections across parts, faulty electronics), errors made by the controller (programming bugs, faulty algorithm), etc. As a consequence, robots might, for example, fail to stop, or a robot arm might achieve high, uncontrolled speed, abrupt motion or acceleration. Accident caused by these errors cannot be predicted even by the most attentive human operator. On the other hand, human accidents, which are more controllable, happen due to various factors, such as inattention, fatigue, inobservance of the guarding procedures, inadequate training programs or incorrect procedures for initial robot start-up.

Adverse environmental factors refer to extreme temperature, poor sensing in difficult weather or lighting conditions, all of which can lead to incorrect response by the robot. Fig. 1 depicts the classifications of accident sources mentioned above. B. Endangered personnel The person who operates the robot is the most at risk. A comprehensive report based on cause-effect analysis of 32 accidents is presented in [3]. Its results show that robot operators were subject to injuries in 72% of the reported accidents. Maintenance workers accounted for 19% of accidents, whereas programmers were least prone to accidents (9% of cases). This directly corresponds to the amount of time a person spends in the proximity of a robot, as well as his or her level of expertise. Robot operators are usually instructed to operate the robots in routine-like situations only, and are therefore unprepared for unexpected robot behavior. Maintenance workers are usually better trained to handle such uncertainty. In many situations, however, they are called when it is already known that the robot is not functioning properly. They therefore maintain a higher level of attention and are more precautious.

Nevertheless, many maintenance workers get injured. These injuries are generally due to human mistakes, such as when another maintenance worker activates a robot system to test it, while the first worker is still in the robot cell. The robot programmers have exceptional knowledge of robot operation, so their injuries often fall into two categories. Most frequently, their injuries are due to unexpected bugs in the software. Less commonly, injuries can occur during the learning procedure. However, they can teach and test robots at lower operating speeds and hence reduce the likelihood of injury. C. Classification of injuries In [3] injuries are classified according to their type between pinch (56%) and impact (44%) injuries. Pinch injury occurs when a robot traps a worker between itself and an object, whereas impact injury occurs when robot and worker collide. Consequences are classified as minor with no lost work-time, lost work-time injuries and fatal injuries. Based on results shown in [3], pinch injuries seem to be of a more serious nature than impact accidents. A more recent approach gives a more detailed classification of contact scenarios that could lead to an accident [4].

Contact can be an unconstrained impact, partially constrained impact, constrained impact, clamping in the robot structure or secondary impact. Fig. 2 depicts these scenarios. Each of these impacts can be with a blunt or a sharp surface. The International Organization for Standardization gives in [5] an extensive classification of hazards based on their origin. Mechanical hazards arise from unexpected or unintended movements, unintended release of tools, rotational motion, trapping of clothes or hair, becoming trapped within the robot cell, etc. Electrical hazards comprise for instance contacts with live parts or connections, or exposure to arc flash. Thermal hazards are associated with hot surfaces or exposure to extreme temperatures required by an ongoing industrial process. Noise hazards are caused by loss of balance, disorientation or inability to coordinate tasks through communication. Other common hazards include vibration, radiation, hazards created by the use of dangerous materials, hazards coming from the dangerous environment in which robot is used (e.g., while trying to avoid a sharp edge, a worker comes in contact with a hot surface), and some combination of these factors.

Hazards associated with robots are well recognized, but the sources of hazards are frequently unique to a particular robot system. Not all of the identified hazards apply to all robots, nor is the level of risk associated with a given hazardous situation the same for each robot. Regulations defined by standards are thus ambiguous and not easily applicable. Designing measures that are robot and context specific may be one way of ensuring safety in constrained settings, such as industrial settings, but it falls short of ensuring safety in HRI in a generic way. This makes the problem of ensuring safety in human-robot interactions difficult.

INDUSTRIAL ROBOTS

Industrial robots were introduced in order to replace human workers performing dangerous, difficult, dull, monotonous and dirty tasks. In the past, these dangerous workplaces caused human workers injury and disease. Some health hazards that affect human workers in workspaces are toxic fumes, heat, radiation, noise, physical injuries and so on. In automated production systems, robots are deployed in large numbers for assembly, handling, welding and coating tasks.

Robots thereby not only improve safety, but also productivity in heavy industry. However, as described in the previous section, robots can also represent a hazard for the people surrounding them. This section emphasizes accidents caused by robots in industry and gives an overview of safety measures proposed by current standards. There are many standardization bodies dealing with the safety in human-robot interactions, but the most influential ones are the International Organization for Standardization (ISO) and the American National Standards Institute (ANSI). ISO 10218 is the most recent set of standards regarding the safety in industrial robots [5], [6]. The European Union has adopted it without any changes. The American standards manual ANSI/RIA R15.06-1999 was made public in 1999 [7]. It is widely used both in the United States and abroad (e.g., it has been translated to

Japanese and used there). It was reaffirmed in 2009 without changes. Its newest version, ANSI/RIA R15.06-2012 is currently undergoing public review and will be made available soon [8].

Accidents related to industrial robots happen most frequently when the human worker is inside the work cell while the robot is operating. Additionally, incidents can occur during servicing or programming the robot. Ideally, robots should be safe to humans regardless of failure or even misuse. In reality, perfect safety records in all contingencies are not feasible for machines that have to deliver performance in terms of cutting, welding, weight lifting, etc. A trade-off between performance and safety is therefore necessary. One of the commonly used safety measures in a robot work cell is constructing a physical safety barrier around the robot. The main purpose of building the barrier is to safeguard the work cell against access by humans, while the robot is in operation. Safeguards can be fixed (e.g., safety fences) or movable (e.g., gates, flaps). Physical safeguards are complemented by non-physical safeguards (e.g., light curtains, scanners and safety mats). The American National Standard for safety requirements in industrial robots explicitly states that the most effective mean of safeguarding against injury is to shut the robot system off upon human entry in the robot work cell [9]. A safety fence usually has one or more gates attached to it, through which humans enter the robot work cell exclusively.

An interlock device is incorporated into the gate, which stops the robot operation if the gate is opened. Closure of the gate does not resume the robot operation automatically. In accordance with [6], automatic operation shall be initiated from outside the safeguarded space and it should only be possible when all associated safeguards are active. Means shall be provided to establish a restricted space around the robot. When it is not feasible to guard the robot work cell, limiting measures shall be used. The robot shall either have mechanical and electro-mechanical axis limiting devices, or software-defined limits to robot motion. Softwaredefined limits define a geometric shape (i.e., zone) that is used to either limit the motion of the robot within its interior, or limit the motion from entering this zone [5].

Danger to the human workers can further be reduced by proper installation of a robot system. By building high floor surfaces for covering the cables, the likelihood of tripping and falling over them is minimized. Restricted and operating spaces shall be established and clearly marked, as well as traffic routes (e.g., pedestrian aisles, visitor routes, etc.). Access and safe pathway to support services (electricity, gas, water), control systems, service and cleaning shall be provided [6]. Special attention needs to be devoted to the recovery from a failure. Loss of power or variations in power shall not result in a hazard. Re-initiation of power must not lead to any motion, as defined in [5]. Upon recovery, robot operation shall be re-initiated manually.

Start and restart of the robot system shall be simple operations, and shall require relevant safety and protective measures to be functional. Location of actuating controls shall be chosen carefully, so as to prevent unintended operation. Status of actuating controls shall be clearly indicated (e.g., power on, fault detected, etc.). In many cases, a collaboration between worker and robot is required. Therefore, it is not always possible to shut the robot off. A good solution is to equip the robot with forcetorque sensor along with a force-torque control techniques, as described in [10], [11]. The force-torque sensor provides the amount and direction of the force and the moment, which is then used to control the robot's movement considering its maximum allowable velocity.

In addition to safety control through force-torque sensors, the robot shall operate at slow speed mode when a human is present in a robot cell. ISO 10218 states that safe slow speed for a robot needs to be limited to 0.25 $m \cdot s^{-1}$. However, the size, configuration and environment of the robot to be guarded change the effectiveness of the safety techniques. Under certain environmental conditions or applications (such as programming or teaching), safe slow speed can be as low as 0.1 $m \cdot s^{-1}$ to 0.2 $m \cdot s^{-1}$ [12]. On the other hand, the authors of [4] criticize the limit of 0.25 $m \cdot s^{-1}$, saying that it is unnecessarily restrictive and as such greatly limits the robots' performance.

In these two examples, the speed limit proposed by the standard does not generalize well to the variety of applications and scenarios. Hence, standards might be too loose and too general to apply easily, or they might require technical expertise beyond the user's capability [13]. To further demonstrate this difficulty, and also illustrate the previously mentioned software-defined limits, we refer to Section 5.12.3 from ISO 10218-1 [5]. It states that once set, safety-rated software limits shall always become activated upon robot power-up. There is, however, a possibility that a person installing a robot does not abide by the installation manual, and thus the software limits never get set. Although the safe speed limits exist, human proximity to the robot can still be dangerous. Motions that pass near singularities can produce high axis speeds, despite the limits.

These high speeds can be unexpected by an operator. Singularities should be avoided if possible. If not, the robot motion should be stopped and a warning should be provided prior to the robot passing through or correcting for a singularity. However, in some cases the singularities can be controlled without creating any hazardous motion [5]. Many approaches that endow the robot work cell with multiple sensors (e.g., proximity sensors, area detectors, cameras) to help determine that a human entered the vicinity of the robot have been studied in the literature. For example, Kulic and Kroft studied approaches that use this information to replan on the fly a path that minimizes chances of collision [14].

There are also industrial products based on the same principle, such as ABB's SafeMove [15]. Despite these achievements, adjusting the plan of the robot on the fly remains a challenge. While there exist control methods to replan on-line trajectories, software of industrial robots is not flexible and relies on predefined trajectories. To endow industrial robots with flexibility will hence require a complete redesign of the software provided currently by the main robotics manufacturers. Apart from ISO 10218, the new ANSI/RIA R.15.06-2012 regulations will also give specific guidelines for collaborative robot applications [8]. It will be the first time that the collaboration is allowed by the American standard since the ANSI/RIA R.15.06-1999 prohibited a man in the loop with a robot in 1999. As the technology advances in terms of safety sensors and robot control, it has allowed man to be reintroduced in the loop.

It will however be an optional feature, only available on new robots and robot systems. The robot shown there serves as a human precision augmentation tool, and stretches from fully automated operation to acting as a servo-controlled balancer. The example shows the heavy gear box, that is grasped by the robot and softly balanced, so that worker can insert it precisely in the housing [16]. There are more potential ways to protect the human operators in the work cell, while loading and unloading the work parts in the processing operations. During this process, a rotary table can be used to transport raw materials from the human workers to the robot and finished work parts back to the workers. A rotary table is advantageous in that it divides the working space of the worker and the robot, reducing the risk of collision with the robot. Despite all the safety measures, accidents can still happen, when least expected. ISO 10218-2 defines that every robot shall have a protective stop function and an independent emergency stop function [6]. It should be located at the minimum (albeit safe) distance, such that the operator has a quick, unobstructed access to it.

Upon collision, robot should perform a safety stop function and remain still until manually reactivated. In this way, the damage it causes will be minimized. However, it is not good practice to have the robot immediately start moving in the other direction, away from the person with whom it came in undesired contact.

In that case, the robot could possibly collide with another person who might be nearby and was not expecting a sudden change in the robot's moving trajectory. Determining adequate reactive behavior when the robot enters in contact with humans is one of the many challenges robotics will have to solve to ensure safety in dynamic environments inhabited with humans. A two-dimensional tactile sensor has the ability to detect pressures and their two-dimensional distribution. Contact sensing provides an important and direct feedback for control, both in cases of voluntary and involuntary interactions with the environment. It can be applied to a robot as an artificial skin and used to safely stop a robot's movements in a human-centric perspective [17]. Tactile sensor placement is very important. It is worth noting that approaches that put tactile sensors along the main segment of the robot do not bring more information than would be provided by a force/torque sensor placed at the joint. Having tactile sensing on parts of the robot segments that bend or retract would be more useful, as it may allow to detect if a human limb got hooked in-between two retractable parts of the robot.

CONCLUSION

Robots are slowly and increasingly pervading in many segments of human lives. They are becoming part of our living environment. While useful, robots also represent a potential hazard. They can move their arms or bodies forcefully and very rapidly, and often manipulate dangerous and sharp tools. This represents a threat to all living agents that are surrounding robots. If humans are present in the robots' proximity, the situation gets even more dangerous. Industrial robots are usually installed inside a guarded work cell and their operation is regulated with standards. Relaxation of some of the rules defined by standards makes the issue of safety a prominent one. Therefore, defining robot and context specific safety guidelines needs to be urgently addressed by the scientific and industrial community. Many experts in the field claim that autonomous vehicles are going to increase traffic safety. Still, they also represent a new threat. Therefore, there is an immediate need for the design of clear guidelines and of safety measures to ensure that these new set of autonomous and semi-autonomous vehicles increase safety on our roads, as opposed to the converse.

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