Robotics Safety: An Engineering Teaching Module

Prepared by:

Guohua Cui, Dan Zhang and Marc A. Rosen Faculty of Engineering and Applied Science University of Ontario Institute of Technology 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

Prepared for:

Minerva Canada http://www.safetymanagementeducation.com

March 2014





Preface and acknowledgements

This document is part of an Engineering Teaching Module on robotic safety developed for Minerva Canada. It is accompanied by a powerpoint teaching aid on the topic, for which this document is intended to provide more detail and greater background.

This Engineering Teaching Module is one of many health and safety engineering student teaching modules developed by Minerva Canada on various topics.

This module was developed with the financial support of Minerva Canada and Mitacs Canada and with the support of General Motors of Canada, an organizational sponsor of the module. We are particularly grateful for the assistance of Ms. Lynn Smith of Engineering Operations and H&S Management at General Motors of Canada.

Contents

Preface and acknowledgements		
Contents	iii	
1. Introduction to robotics safety	1	
2. Types of robots and industrial robots	3	
2.1. Definition of robots and industrial robots	3	
2.2. Classifications of robots	4	
2.2.1. Classification based on design configuration	4	
2.2.2. Classification based on control systems	6	
2.2.3. Classification based on path generation	7	
2.3. Industrial robot components	7	
2.3.1. Mechanical unit	8	
2.3.2. Power source	8	
2.3.3. Control system	8	
3. Types and sources of robotics hazards	10	
3.1. Types of robot accidents		
3.2 Examples of robot accidents	10	
3.3. Sources of hazards	10	
3.4. Case studies: Incidents and Lessons Learned	10	
3.4.1. Machine Operator Crushed by Robotic Platform	12	
3.4.2. Mold Setter's Head Struck by Cycling Single-side Gantry Robot	13	
3.4.3. Die Cast Operator Pinned by Robot	14	
4. Robot safety requirements	16	
4.1. Requirements and safety measures in normal operation	16	
4.2. Demands and safety measures in special operation modes	16	
4.3. Demands on safety control systems	17	
5. Robot safeguards	18	
5.1. Robot safeguards from design to operation	18	
5.1.1. Risk assessment	18	
5.1.2. Robot safety begins with the design process	18	
5.2. Robot safeguards and engineering applications	20	
5.2.1. Today's safeguarding methods	20	
5.2.2. Instruction to improve robot safety	26	
5.2.3. Typical engineering applications	27	

6. Robot safety standards	
6.1. Technology and standardization development overview	31
6.2. Current standards for robotic safety	32
References	34

1 Introduction to robotics safety

Robots are widely used in industry. They can perform unsafe, hazardous, highly repetitive and unpleasant tasks for humans. Furthermore, industrial robots, unlike humans, can perform complex or mundane tasks without tiring, and they can work in hazardous conditions that would pose risks to humans. Nowadays, industrial robots have been widely introduced to production lines and are expected to find more applications in the future. This is primarily due to the many merits of industrial robots that conventional machines do not possess. For example, robots are increasingly being used in industry to perform such tasks as material handling and welding, and there are around one million robots in use worldwide [1]. However, robots can pose hazardous risks to humans if sufficient precautions are not provided.

Safety is a key factor in industrial and service robot applications, making robotics safety an important subject for engineers. For instance, around 12-17% of accidents in industries using advanced manufacturing technologies have been reported to be related to automated production equipment, including robots. Some important examples and data concerning robot safety follow [1]:

- The first robot-induced fatal accident occurred in Japan in 1978.
- In one incident, a worker entered a robot work cell by overriding safety devices while a material handling robot was operating in its automatic mode. The worker became trapped between the robot and an anchored post and was injured.
- In another incident, a maintenance person climbed over a safety fence without turning off the power to the robot, and performed tasks in the robot work zone while the robot was temporarily stopped. When the robot recommenced operation, it pushed the person into a grinding machine, killing the person.

Robot safety may be interpreted in various ways, including preventing the robot from damaging its environment, particularly the human element of that environment, and simply preventing damage to the robot itself. Without proper precautions, a robot experiencing a fault or failure can cause serious injuries to people and damage equipment in or around a work cell.

Industrial robots are programmable units designed to form expected movements but, unfortunately, the movements of people who work with robots cannot be predicted, making robot safety very important. Most robot-related accidents occur during programming, maintenance, repair, setup and testing. All of these tasks involve human interaction, necessitating proper safety training for employees and the proper use of appropriate safeguards.

Note that robots, depending on the task, may generate paint mist, welding fumes, plastic fumes, etc. Also,, robots, on occasion, are used in environments or tasks too dangerous for workers, and as such creates hazards not specific to the robot but specific to the task.

Robotics safety operates under a set of principles, primarily related to how to protect humans from robot motions. Fig. 1 shows a robot safety system.



Fig. 1 - An effective robot safety system [2]

The principles of robotics safety and the systems to be used when working with robotics are covered in this engineering teaching module.

2 Types of robots and industrial robots

2.1 Definition of robots and industrial robots

A robot is a mechanical or virtual intelligent agent that can perform tasks automatically or with guidance by remote control. A robot typically has the capacity for sensory input (vision, touch, etc.), recognition and movement, which means a robot should at least have sensors, motors and controllers. There are several types of robots, often differentiated based on function, axis, degree of freedom, workspace, etc. The main types of robots today include, but are not limited to, industrial robots (Fig. 2), military robots (Fig. 3, left), medical robots [6] (Fig. 3, right), mobile robots, service robots, and micro and nano robots.



Fig. 2 - Industrial robots in factories [3,4]



Fig. 3 - Military robots (left) [5] and medical robots (right)

Industrial robots are, multifunctional, mechanical devices, programmable in three or more axes, designed to move material, parts, tools or specialized devices through variable programmed motions to perform a variety of tasks. They have many functions such as material handling, assembly, arc welding, resistance welding, machine tool loading and unloading, etc.

An industrial robot system includes not only industrial robots but also related devices

and/or sensors required for the robot to perform its tasks, as well as sequencing and monitoring communication interfaces.

2.2 Classifications of robots

Robots can be classified according to various aspects, such as design configuration, control system, path generation, and others.

2.2.1 Classification based on design configuration

Various robot design configurations [2], which are included in this classification, are shown in Figs. 4-10.

Cartesian coordinate robots

A Cartesian coordinate robot has three linear axes of control (x, y, z), as shown in Fig. 4. Cartesian coordinate robots with the horizontal member supported at both ends are sometimes called gantry robots.



Fig. 4 - Cartesian coordinate robot [7]

Cylindrical robots

A cylindrical robot has two linear axes and one rotary axis around its origin, as shown in Fig. 5.



Fig. 5 - Cylindrical robot [7]

Spherical/Polar robots

Spherical and polar robots have one linear axis and two rotary axes, as shown in Fig. 6.



Fig. 6 - Spherical/polar robot [7]

SCARA robots

SCARA (Selective Compliance Assembly Robot Arm) is a particular robot design developed in the late 1970s in Japan. The basic configuration of a SCARA is a four degree-of-freedom robot with horizontal positioning accomplished by combined θ_1 and θ_2 motions, as shown in Fig. 7, much like a shoulder and elbow held parallel to the ground. SCARA robots are known for their fast cycle times, excellent repeatability, good payload capacity and large workspace.



Fig. 7 - SCARA robot [7]

Delta robots

The key design feature of delta robots is the use of parallelograms in the arms, which maintain the orientation of the end effector, as shown in Fig. 8. Such robots have three translational degrees of freedom. In addition, there is a rotational axis provided at the end effector. As the delta robot is a type of parallel robot, the weight of the load is distributed over the arms and similarly any errors are averaged over the legs.



Fig. 8 - Delta robot [7]

Articulated/joint-arm robots

Articulated or joint-arm robots are the most versatile of robots. They closely mimic the natural form of the human arm, and can be treated as a shoulder, a bicep and a forearm, but often without a wrist, as shown in Fig. 9. A six-axis robot includes a wrist, providing pitch, roll and yaw movements. With the extra axes of motion provided by the wrist, this robot can deliver the end effector to any point in space in any orientation.



Fig. 9 - Articulated/jointed-arm robot [7]

Snake arm robots

Snake arm robots are flexible manipulators. The name is based on their ability to follow the front of the robot around and through obstacles in a snake-like fashion. Such robots are constructed in much the same way as the human spine via a number of interconnected vertebrae, as shown in Fig. 10. Drive wires are used to pull the body in a certain direction and terminate at different points along the length. The length of the wires is controlled within the drive unit at the base of the robot arm by a series of servo-actuators.



Fig. 10 - Snake arm robot [7]

2.2.2 Classification based on control systems

All industrial robots are either servo or non-servo controlled [8], and they can be classified based on their method of control.

Servo robots

Servo robots are controlled through the use of sensors that continually monitor the robot's axes and associated components for position and velocity. This feedback is compared to the desired information which has been programmed and stored in the robot's memory. The motors are actuated to move the actuator to the desired position/speed.

Non-servo robots

Non-servo robots do not have feedback capability, and their axes are controlled through a system of mechanical stops and limit switches.

2.2.3 Classification based on path generation

Point-to-Point path

Such robots are programmed and controlled to move from one discrete point to another within the robot's working envelope [8]. In the automatic mode of operation, the exact path taken by the robot may vary slightly due to variations in velocity, joint geometries and point spatial locations. This difference in paths is difficult to predict and therefore can create a potential hazards to personnel and equipment.

Controlled path

The path or mode of movement ensures that the end of the robot's arm will follow a predictable (controlled) path and orientation as the robot travels from point to point [8]. The coordinate transformations required for this hardware management are calculated by the robot's control system computer. Robots that utilize this type of programming are less likely to present a hazard to personnel and equipment.

Continuous path

A robot whose path is controlled by storing a large number or close succession of spatial points in memory during a teaching sequence is a continuous path controlled robot [8]. During this time, the coordinate points in space of each axis are continually monitored on a fixed time base while the robot is being moved, e.g., 60 or more times per second. When the robot is placed in an automatic mode of operation, the program is replayed from memory and a duplicate path is generated.

2.3 Industrial robot components

Industrial robots have four major components: mechanical unit, power source, control system and tooling [8], as shown in Fig. 11.



Fig. 11 – The four major components of an industrial robot

2.3.1 Mechanical unit

The robot's manipulative arm is the mechanical unit. This mechanical unit is comprised of a fabricated structural frame with provisions for supporting mechanical linkages, joints, guides, actuators (linear or rotary), control valves and sensors. The physical dimensions, design and weight-carrying ability depend on application requirements.

2.3.2 Power source

Energy is provided to various robot actuators and their controllers as pneumatic, hydraulic or electrical power. The robot's drives are usually mechanical combinations, and the selection of a power source is usually based on the requirements of a given application, as described below:

- Pneumatic power (usually low-pressure air) is generally used for low weight carrying robots.
- Hydraulic power transmission (usually high-pressure oil) is often used for medium to high force or weight applications, or where smoother motion control can be achieved than with pneumatics. Consideration should be given to potential hazards caused by leaks if petroleum-based oils are used.
- Electrically powered robots are the most prevalent in industry. Either AC or DC electrical power is used to supply energy to electromechanical actuating mechanisms and their respective control systems. Motion control is much better, and in an emergency an electrically powered robot can be stopped or powered down more safely and quickly than robots driven by either pneumatic or hydraulic power.

2.3.3 Control system

Either auxiliary computers or embedded microprocessors are used for the control of almost all industrial robots today. These perform all of required computational functions, as well as interface with and control associated sensors, grippers, tooling and other associated peripheral equipment. The control system performs the necessary sequencing and memory functions for on-line sensing, branching and integration of other equipment. Programming of the controllers can be done on-line or at remote off-line control stations with electronic data transfer of programs.

Self-diagnostic capability for troubleshooting and maintenance greatly reduces robot system downtime. Some robot controllers have sufficient capability in terms of computational ability, memory capacity and input-output capability to serve also as system controllers and handle many other machines and processes. Programming of robot controllers and systems has not been standardized by the robotics industry, so manufacturers usually use their own proprietary programming languages which require special training of personnel.

3 Types and sources of robotics hazards

3.1 Types of robot accidents

Robotic safety incidents typically occur when a robotic arm or controlled tool causes an accident and/or places an individual in a risk circumstance, an accessory of the robot's mechanical parts fails, or the power supplies to the robot are uncontrolled [9]. Robotic incidents can be grouped into four categories [9]:

- 1. **Impact or collision accidents**: Unpredicted movements, component malfunctions or unpredicted program changes related to the robot's arm or peripheral equipment can result in contact accidents.
- 2. **Crushing and trapping accidents**: A worker's limb or other body part can be trapped between a robot's arm and other peripheral equipment, or the individual may be physically driven into and crushed by other peripheral equipment.
- 3. **Mechanical part accidents**: A breakdown of the robot's drive components, tooling or end-effector, peripheral equipment, or power source can lead to a mechanical accident. The release of parts, failure of gripper mechanism, or the failure of end-effector power tools (e.g., grinding wheels, buffing wheels, deburring tools, power screwdrivers and nut runners) are a few types of mechanical failures.
- 4. **Other accidents**: Other accidents can result from working with robots. Equipment that supplies robot power and control represents potential electrical and pressurized fluid hazards. Ruptured hydraulic lines can create dangerous high-pressure cutting streams or whipping hose hazards. Environmental accidents from arc ash, metal spatter, dust, and electromagnetic or radio-frequency interference can also occur. In addition, equipment and power cables on the floor present tripping hazards.

3.2 Examples of robot accidents

Studies indicate that many robot accidents do not occur under normal operating conditions, but rather during programming, program touch-up, maintenance, repair, testing, setup or adjustment. During many of these operations the operator, programmer or corrective maintenance worker may temporarily be within the robot's working envelope where unintended operations could potentially result in injuries.

Examples of some robot accidents that have been reported follow:

• **Example 1:** The first fatal robot-related accident in the United States occurred in 1984. On July 21 of that year, a die cast operator was working with an automated die cast system that utilized a Unimate Robot. The robot was programmed to extract the casting from the die-cast machine, dip it into a quench tank and then insert it into an automatic trim press. A neighboring employee discovered the victim pinned between the right rear of the robot and a safety pole in a slumped

but upright position. The victim died five days later in the hospital.

- **Example 2:** A material handling robot was operating in its automatic mode and a worker violated safety devices to enter robot work cell. The worker became trapped between the robot and a post anchored to the floor. Consequently, the worker was injured and died a few days later.
- **Example 3:** A maintenance person climbed over a safety fence without turning off robot power and performed tasks in robot work zone while the robot was temporarily stopped. When it recommenced operation, it pushed the person into a grinding machine and the person died.

Numerous other robot accidents have been reported, as described below:

- In 2000, the head of a person was crushed between a conveyor and a robot. The task of the robot was to feed cows at a farm.
- In 2005, a person was crushed between a manipulator (resembling a gantry type robot) and a conveyor. The task of the manipulator was to move bricks from one conveyor to another at a brick factory.
- In 2006, a person was crushed between a robot and a conveyor. The task of the robot was to move trays to a conveyor, in an application in the dairy industry.

3.3 Sources of hazards

The potential hazards posed by machines to humans can be assessed and broken down by source/cause, as follows: human interaction, control error, unauthorized access, mechanical failure, environmental source, power system fault and improper installation [8]. Each of these is examined below.

- **Human interaction**: Hazards from human interaction associated with programming, interfacing activated peripheral equipment, or connecting live input-output sensors to a microprocessor or a peripheral device, can cause dangerous, unpredicted movement or action by a robot. The incorrect activation of the "teach pendant" or control panel is an example of human interaction. One of the greatest hazards is over-familiarity with the robot's redundant motions, so that an individual places herself/himself in a hazardous position while programming the robot or performing maintenance on it.
- **Control errors**: Intrinsic faults within the control system of the robot, errors in software, and electromagnetic interference are possible control errors. These errors can also occur due to faults in the hydraulic, pneumatic or electrical sub-controls associated with the robot or robot system.
- Unauthorized access: Entry into a robot's safeguarded area is generally potentially hazardous. This hazard is more pronounced when the person involved is not familiar with the safeguards in place or their activation status.
- **Mechanical failures**: Operating programs may not account for cumulative mechanical part failure, which can allow faulty or unexpected operation to occur.

- **Environmental sources**: Electromagnetic interference (transient signals) can exert an undesirable influence on robotic operation and increase the potential for injury to any person working in the area. Means of addressing the environmental hazards should be documented prior to equipment start-up.
- **Power systems**: Pneumatic, hydraulic or electrical power sources that have malfunctioning control or transmission elements in the robot power system can disrupt electrical signals to the control and/or power-supply lines. Fire risks exist due to the potential for electrical overloads and the use of flammable hydraulic oil. Electrical shock and release of stored energy from accumulating devices also can be hazardous to personnel.
- **Improper installation**: The design, requirements, layout of equipment, utilities, and facilities of a robot or robot system, if inadequate, can lead to inherent hazards.

Note that this list is not in any particular order (e.g., order of importance or highest frequency). There exist many sources of hazards and, in fact, the highest frequency occurrences may vary by industry. Ongoing improvements in error-proofing technology and overall robot design are lessening the hazards involving humans and robots.

3.4 Case studies: Incidents and Lessons Learned

Building on the examples listed in section 3.2, several case studies are presented, in this section, which describe actual incidents involving robots and the lessons learned from them. These are based on reports on the web site of the Occupational Safety & Health Administration of the U.S. Department of Labor (https://www.osha.gov/SLTC/robotics/).

3.4.1 Machine Operator Crushed by Robotic Platform (Nebraska, 1999)

A summary follows of the incident covered in this case study, along with lessons learned in the form of recommendations that resulted from the investigation. These materials are listed, along with other details, on the relevant web page (http://www.cdc.gov/niosh/face/stateface/ne/99ne017.html).

Incident: "A 23-year-old carousel operator, at a meat packing plant, was killed when his foot tripped a light sensor causing a computer controlled robotic platform to come down from above, crushing his skull. He had been watching a maintenance technician work on a conveyor and apparently stepped on the conveyor to get a better view of what the mechanic was doing. The conveyor the mechanic was working on had been shut off but the entire system had not been locked out. Power still remained to the light sensors and the robotic platform. When the platform came down it pinned the victim between the platform and the conveyor. When they lifted the platform off the victim, the victim fell approximately 15 feet to the concrete floor below. Death was most likely caused by the blow to the head from the robotic platform, not the fall. The victim was pronounced dead at the scene."

Lessons learned: The Nebraska Department of Labor investigated the incident and its investigator concluded that, to prevent similar occurrences in the future, employers should:

- "ensure all equipment is properly locked out/tagged out prior to performing maintenance on it.
- consider implementing a spot inspection program to ensure all employees are complying with safety requirements.
- develop procedures to ensure individuals not involved in maintenance activities are not in the immediate area of the maintenance being performed.
- consider installing a protective grate around access areas to the robotic platform."

3.4.2 Mold Setter's Head Struck by Cycling Single-side Gantry Robot (Michigan, 2001)

A summary of the incident and lessons learned in case study, as listed with other details on the relevant web page (http://www.cdc.gov/niosh/face/stateface/mi/01mi002.html), follows:

Incident: "On January 19, 2001, a 29-year old male died from injuries sustained when he was struck on the head by a cycling single-side gantry robot. The victim had recently performed a mold change on a 1500-ton horizontal injection-molding machine (HIMM). He was apparently looking for tools that he may have left within the machine during the set-up operation. The victim climbed on top of the purge guard and leaned over the top of the stationary platen of the HIMM in an attempt to see if the tools were left within the mold area, and placed his head beneath the robot's gantry frame. His position placed him between the robot's home position and the robot's support frame on the stationary platen. While trying to look inside the mold area, the robot cycled, and the victim's head was struck from the side and crushed between the robot and the robot's support frame. Another employee noticed the victim on top of the HIMM and went to investigate. Upon seeing the victim's condition, fellow employees were called to move the victim to the floor. Emergency responders were called, and awaiting emergency responder arrival, employees began chest compressions and other first aid procedures. The victim was pronounced dead on arrival at the local hospital."

Lessons learned: The recommendations that were made after the investigation of this incident follow:

• "The robot and the point of operation should be safeguarded to prevent entry during

automatic operation.

- Users should conduct a risk assessment of the robot/robot system to identify equipment, installation, standards, and process hazards so adequate employee safeguards are provided.
- Users should ensure that personnel who interact with the robot or robot system, such as programmers, teachers, operators and maintenance personnel are trained on the safety issues associated with the task, robot and robot system."

3.4.3 Die Cast Operator Pinned by Robot (Michigan, 1984)

A summary follows of the incident in case study along with lessons learned in the form of conclusions and recommendations. This information and other details are on the relevant web page (http://www.cdc.gov/niosh/face/In-house/full8420.html).

Incident: "On July 21, 1984 a 34 year old die cast operator with 15 years experience went into cardiopulmonary arrest after being pinned between the right rear end of a hydraulic robot and a safety pole. Rescue efforts included unpinning the worker, administering CPR, and transporting him to the emergency room of a nearby hospital. Five days later, he was pronounced dead as a result of cerebral necrosis.... On the day of the incident, the die cast operator was working with an automated die cast system that utilized a Unimate Robot. This robot was programmed to extract the casting from-the die-cast machine, dip it into a quench tank and then insert it into an automatic trim press. The robot is programmed to perform the entire cycle in 27 steps which take approximately one minute. The safeguard present included a safety rail with interlock gate. At approximately 1:00 PM, the victim entered the working area of the robot by either climbing over/through the safety rail or by walking through one of the unguarded gaps between the safety rail and related die-casting equipment. His reason for entering the robot work envelope is uncertain. Several workers believed that since he had an air gun with him, he may have been trying to clean up 'flash' and scrap metal that had accumulated on the floor. Fellow workers also stated that they had seen the die-cast operator inside the work envelope on previous occasions with the robot up and running. The die-cast operator had been trained against this prohibited activity at the manufacturer's training course on the robot. He had recently attended the course from June 25, 1984 to July 1, 1984."

Lessons learned: The conclusions drawn from the investigation of this incident follow: "At the time of the accident, the victim was an experienced die cast operator who received both classroom training and on-the-job instruction on robotic safety. He had been both previously observed inside the envelope while the robot was running and verbally warned against this practice by fellow workers. The major factor contributing to this fatal accident may have been the behavior of the victim."

The general recommendations drawn from the investigation of this incident, which are applicable to all facilities and workers that use or anticipate using robots, follow:

- *"Ergonomic Design*: (1) Safety fences with interlocking gates rather than rails should be used to fence off active robots. The purpose of the fence is to prevent unauthorized entry into the range of the robot's moving parts. (2) Free-standing steel posts, designed to restrict the movement of the robot's arm in case a 'loss of control' is experienced, may provide man-sized pinch points where an unsuspecting worker could become trapped.
- Training: Extensive training should be provided for employees who will be • programming, operating or maintaining robots. This training should be safety-oriented as well at instructing employees in the methods of programming, starting up and stopping the robot. Newly trained employees may require close supervision until they adjust to the robot. Specific aspects of any training program should include/stress the following points: (1) Operators should never be in the work envelope while the robot is operational. (2) Because programming must be done inside the work envelope while the robot is operational, programmers should operate the robot at a slow safe speed be made aware of all the possible pinch points where his body or extremities could be trapped. (3) Training is not only needed for the inexperienced workers but refresher courses should be provided for experienced robot programmers and operators as well. (4) During programming, the robot should be stopped at each intermediate step and all possible pinch points should be identified and eliminated if possible. (5) During the safety and training course the following statements should be emphasized: 'If the robot is stopped, don't assume that it will remain stopped', and 'If a robot is repeating a motion, don't assume that it will continue to repeat only that motion.'
- *Supervision*: (1) Strict enforcement of a set of clearly written safety rules that reflect the company's own safety program is essential to ensure the protection of the worker. Disciplinary action should be taken against anyone who enters the work envelope without first putting the robot on hold or in a 'power down' condition. (2) Supervisors should be cognizant of the fact that operators experienced at automated tasks may be become bored, overconfident, or lose concern for safety. These conditions may increase the worker's risk of injury."

4 Robot safety requirements

Statistics from investigations indicate that the majority of industrial robot incidents and accidents do not take place during normal operation. When working with industrial robots and installations, there is an emphasis on special operation modes, such as commissioning, setting up, programming, testing, checking, troubleshooting and maintenance. In these operating modes, personnel are usually in a danger zone, so safety measures are required to protect them from hazardous events.

4.1 Requirements and safety measures in normal operation

The use of robot technology necessitates hazard analysis, risk assessment and safety measures. The following examples and suggestions can serve as guidelines [10]:

- 1. Possible measures to prevent physical access to hazardous areas involving automatic movements include the following:
 - Prevent manual or physical access into danger zones by means of mechanical barriers.
 - Use safety devices that respond when approached (light barriers, safety mats), and take care to switch off machinery safely when accessed or entered.
 - Permit manual or physical access only when the entire system is in a safe state. For example, this can be achieved by the use of interlocking devices with closure mechanisms on access doors.
- 2. Possible measures to prevent injuries as a result of the release of energy include the following:
 - Designs should prevent any release of energy.
 - Measures can be added to prevent the release of energy from the danger zone, for example, by a correspondingly dimensioned safety hood.
 - Proper lock out and/or tag out procedures need to be utilized to ensure all hazardous energy sources have been isolated.
- 3. Interfaces can be applied between normal operation and special operation (e.g., door interlocking devices, light barriers, safety mats) to enable the safety control system to automatically recognize the presence of personnel.

4.2 Demands and safety measures in special operation modes

Certain special operation modes (e.g., setting up, programming) of an industrial robot require movements which must be assessed directly at the site of operation. None of these movements should endanger the persons involved. With this objective in mind, the movements should be [10]

- only of the scheduled type and speed.
- prolonged only as long as instructed.
- performed only if it can be guaranteed that no parts of the human body are in the

danger zone.

One suggested measure to support this goal involves the use of special operating control systems which permit only controllable and manageable movements using acknowledgeable controls. The speed of movement is thus safely reduced (energy reduction by the connection of an isolation transformer or the use of fail-safe state monitoring equipment) and the safe condition is acknowledged before the control is allowed to activate.

4.3 Demands on safety control systems

An important feature of a safety control system is that the required safety function should be guaranteed as much as possible to work whenever any faults arise. Industrial robots should be almost instantaneously directed by such controllers from a hazardous state to a safe state.

Safety control measures should be designed with the following safety objectives in mind [10]:

- A fault in the safety control system should not trigger a hazardous state.
- A fault in the safety control system should be identified (immediately or at intervals).

Suggested measures to provide reliable safety control systems include the following:

- Redundant and diverse layouts of electromechanical control systems, including test circuits.
- Redundant and diverse set-ups of microprocessor control systems developed by different teams. This modern approach is considered state-of-the-art, and often includes safety light barriers.
- Redundant control systems that take in account mechanical as well as electrical failures.

5 Robot safeguards

5.1 Robot safeguards from design to operation

5.1.1 Risk assessment

The first step in designing a safe robot system is to understand the hazards that exist in the system [11]. The hazards can be classified based on the following criteria: severity, potential injury, frequency of access to the hazard and the possibility of avoidance. Different systems and personnel safeguarding requirements exist at each stage in the development of a robot and robot system. At each stage, a risk assessment should be performed. A robot system design concept, which can account for safety, should include the following elements:

- Limits of the robot system
- Task identification
- User considerations
- Hazardous energy control

5.1.2 Robot safety begins with the design process

Safeguards should be designed into and around the robotic cell early in the design process to maximize the inherent safety of the overall system. System designers must understand current safeguarding technology. It is also worth appreciating how this technology can save time and money both now and in the future.

Perimeter guarding

To keep unnecessary personnel out of the restricted space of a robot cell, the following two safeguarding methods are often used [11]:

- **Hard-guarding**: Hard-guarding is a fencing-type solution. With hard-guards, door access is likely to be needed, and these doors must contain interlocking devices (e.g., safety interlocks) to guarantee safe access.
- **Optical perimeter guards**: Optical perimeter guards (e.g., light curtains) are a more flexible safety measure that can easily adapt to layout changes. These guards must be located at a safe distance from the hazard and must interface with the robotic control system.

Optical perimeter guards are often used in combination with hard-guards. An additional requirement for perimeter safety is that operator control needs to be located outside the safeguarded area.

Protection on the inside

If there is a danger to the operator, maintenance personnel or other personnel from robotic motion within the restricted or operating space, this area must also be safeguarded. Area safety scanners and light curtains are often used in these areas, as the scanner coverage area is wider and more flexibly programmed than with other devices. Again, these safeguarding devices must be located at a distance that provides adequate stopping time of the system and accounts for the speed of approach from the personnel in the area as well as a depth penetration factor, as defined in the ANSI/RIA R15.06-1999 standard.

Safeguarding considerations for other stages

For the planning stage, installation and subsequent operation of a robot or robot system, the following need to be considered [8]:

1. Safeguarding devices

Personnel should be safeguarded from hazards associated with the restricted envelope (space) through use of one or more safeguarding devices, such as:

- Mechanical limiting devices
- Non-mechanical limiting devices
- Presence-sensing safeguarding devices
- Fixed barriers (which prevent contact with moving parts)
- Interlocked barrier guards

2. Awareness devices

Typical awareness devices include chain or rope barriers with supporting stanchions or flashing lights, signs, whistles and horns. These are usually used in conjunction with other safeguarding devices.

3. Safeguarding the teacher

Special consideration must be given to the teacher or person who is programming the robot. When systems are large and complex, it can be easy to activate improper functions or sequence functions improperly. Since the person doing the training can be within the robot's restricted envelope, such mistakes can result in accidents. Mistakes in programming can result in unintended movement or actions with similar results. For this reason, a restricted speed of 250 mm (10 in) should be placed on any parts of the robot during training to minimize potential injuries to teaching personnel. Several other safeguards are suggested in the ANSI/RIA R15.06-1992 standard to reduce the hazards associated with teaching a robotic system.

4. Operator safeguards

The system operator should be protected from all hazards during operations performed by a robot. When the robot is operating automatically, all safeguarding devices should be activated, and at no time should any part of the operator's body be within the robot's safeguarded area. The ANSI/RIA R15.06-1992 standard (section 6.6) provides additional operator safeguarding suggestions.

5. Attended continuous operation

When a person is permitted to be in or near a robot's restricted envelope to evaluate or check the robot's motion or other operations, all continuous operation safeguards must be in force. During this operation, the robot should be at slow speed, and the operator should have the robot in the teach mode and be fully in control of all operations. Other safeguarding requirements are suggested in the ANSI/RIA

R15.06-1992 standard (section 6.7).

6. Maintenance and repair personnel

When maintenance and repair are being performed, the robot should be placed in the manual or teach mode, and the maintenance personnel should perform their work within the safeguarded area and outside the robot's restricted envelope. Additional safeguarding techniques and procedures to protect maintenance and repair personnel are listed in the ANSI/RIA R15.06-1992 standard (section 6.8).

7. Safety training

The user of a robot should be well-trained, particularly regarding the use of safety equipment and procedures. Users must be aware of the possible hazards and should have an overview of the entire application. Robotic programmers and engineers should be aware that they can cause a hazard when a robot system is programmed or configured in the wrong way. Therefore, they should be familiar with the safety information on the manipulator and control system.

5.2 Robot safeguards and engineering applications

The measures taken to safeguard a robot depend on the circumstances of its operation and the surrounding environment.

5.2.1 Today's safeguarding methods

Fences are used to prevent entry to a robot's working space, as shown in Figs. 12 and 13 (right). The fence also provides a preventive barrier against losing parts from the gripper. Barriers are a different type of protection preventing the worker from entering the cell through the load/unload area, as shown in Fig. 13 (left). In special cases, like laser cutting, arc welding and water jet applications, the system should be completely encapsulated [12].



Fig. 12 – Safeguards for robots

An effective safety system protects operators, engineers, programmers, maintenance personnel and others who could be exposed to hazards associated with a robot's operation. A combination of methods may be used to develop an effective safety system. Redundancy and backup systems are recommended, especially if a robot can create significantly hazardous conditions.

Perimeter fencing

As shown in Fig. 14, a fixed barrier guard is a fence that requires tools for removal. Barrier guards are appropriate safeguards for full-revolution and part-revolution mechanical power presses. Barrier guards are designed to keep the operator's hands and arms from entering the "danger zone" as prescribed by the particular machine. Barrier guards are usually the first point-of-operation safeguard considered for machines.



Fig. 13 - Perimeter barrier (left) and fencing (right) for a robot



Fig. 14 - Fixed barrier guard on a power press [13]

Interlocking devices

Guard-operated interlocking devices, key interlocking devices (transfer of key from control to access gate) and solenoid locks are all types of interlocking devices [13]. As shown in Fig. 15, an interlocking device is a physical barrier around a robot's work envelope that incorporates gates equipped with interlocks.



Fig. 15 - Interlocked barrier guard and interlocks

Presence sensing devices

Presence detectors are commonly used in robotics safety, and are usually pressure mats and light curtains [14]. Floor mats (pressure-sensitive mats), light curtains (similar to arrays of photocells) and laser scanners can be used to detect a person stepping into a hazardous area near a robot. Effective presence sensing devices stop all motion of the robot if any part of a worker's body enters the protected zone. They are also designed to be fail-safe so that the occurrence of a failure within the device will leave it unaffected or convert it to a mode in which its failed state would not result in an accident. In some cases this means deactivation of the robot. Factors that are considered in the selection of such devices include the spatial limitations of the field, the environmental conditions affecting the reliability of the field and the sensing field interference due to robot operation. Details on different types of presence sensing devices follow:

• Light curtains (Fig. 16). If an obstruction is detected within the path of the light beam, an output is triggered. This method provides instant access to the workspace, and multiple instances can provide different safety zones. However they cannot shield against projectile hazards.



Fig. 16 - Safety light curtains

• Laser scanning devices (Fig. 17). These devices use a single laser beam to map an area and detect any changes which would signify a potential hazard, and trigger an output. These devices normally operate below the working level of the robot.



Fig. 17 - Access area safeguarding with laser safety scanner

• Pressure-sensitive mats (Fig. 18). These trigger an output if pressure is applied to the surface. Length of stride, speed of approach and system response time must be considered in placement.



Fig. 18 - Pressure-sensitive mats

Audible and visible warning systems

Audible and visible warning systems are not acceptable safeguarding methods for robots, but may be used to enhance the effectiveness of positive safeguards.

Manipulator position indication and limiting

In every use of a robot system there is a connection to external safety devices. These connections can control the robot system from external devices like a PLC. But in all cases, a robot system should have a connection to external safety devices, like door locks, light barriers and safety scanners, to ensure that the robot can be stopped in a safe way.

There are various ways to limit the robot working area or indicate the area in which the robot can safely move. Traditionally, mainly mechanical measures were utilized to provide these features, but today it is possible to use completely electronic solutions. Some limiting safety options follow.

• **Mechanical limits**: Mechanical limits (Fig. 19) are used to reduce the working area for a robot. Historically, the fences around a robot system have been located outside the robot's maximum workspace. Due to the complexities of cell layout design, it was in most cases not possible to mechanically reduce the working area of the manipulator. In particular, the bending backwards kinematics is extremely difficult to limit to the working range of axis 2 and 3 because the robot's working range is needed for the front area, but it should be limited in the area behind it [12].



Fig. 19 - Mechanical limits

• **Position switch**: A position switch (Fig. 20) is used to indicate where the robot is working at a given instant. In traditional robots, there are position switches for axes 1, 2 and 3 to indicate whether the robot is entering the area or not. This is used for machine protection and/or for personal safety if the robot and the worker have the same workspace.



Fig. 20 - Position switch axis 1 [12]

• Limit switch: A limit switch (Fig. 21) is an additional device that can be connected to a robot system. This is typically used if the robot is standing on a track to safely limit the external axis movement.



Fig. 21 - Limit switch [12]

Enabling devices

An enabling device (Fig. 22) is used in conjunction with other devices to ensure that operation cannot begin unless the device is actuated.



Fig. 22 - Separate enabling device [10]

Other safeguard devices

Various other safeguards can be employed, including the following:

- **Trip devices**: Trip wires can be used to trigger outputs.
- **Positive stops**: These limit the movement of a robot to exclude the area required by an operator.
- **Brakes**: Brakes can be used to support the weight of the arm and object in the event of a power failure.
- **Emergency stop buttons**: The emergency stop is used for immediate stoppage of the machine in case of a hazard, and must be located properly so that it is within easy reach at all times (Fig. 23).
- General stops: A general stop operates as a stop in either manual full speed or automatic mode.



Fig. 23 - Emergency stop buttons and safety light curtain [15]

5.2.2 Instruction to improve robot safety

According to the Occupational Safety & Health Administration (OSHA), most accidents with robots occur during programming, maintenance, repair, setup and testing, all of which involve human interaction. To reduce accidents and improve robot safety, it is important to implement the following industrial robot safety tips [16]:

- Use boundary warning devices, barriers and interlocks around robot systems.
- Provide annual robot safety training for employees working on the floor with robots.
- Provide work cell operators with training geared toward their particular robot.
- Create and implement a preventive maintenance program for robots and work cells;
- Ensure operators read and understand robot system documentation, including that related to robot safety.
- Allow only capable employees who know the safety requirements for working with a robot to operate robot systems.

Along with implementing industrial robot safety practices for a facility and its personnel, it is important to ensure the robotic work cell satisfies the following requirements:

- The maximum reach of a robot should be marked on the floor with safety tape or paint.
- A flashing warning device must be visible from any point around the work cell.
- Safety curtains, fences or work cell equipment should be used as barriers around the cell to protect employees.
- Emergency stop buttons should be located around the cell.

The ISO (International Organization for Standardization) published new safety standards on July 1, 2011. One notable addition is the new standard for risk

assessment. Risk assessment is a process in which one identifies hazards, analyzes or evaluates the risks associated with the hazards, and determines appropriate ways to eliminate or control the hazards. Risk assessment must now be completed when planning and integrating robot systems. The importance of evaluating each device's risk is an important factor in risk assessment, as no two robot systems are alike.

5.2.3 Typical engineering applications

ABB SafeMove

SafeMove is intended to be a major step in removing the restrictions placed on regulated industrial robots that operate in isolated settings, and to represent the next generation in robot safety [17]. Developed and tested to comply with international safety standards, SafeMove is an electronics- and software-based safety approach that ensures safe and predictable robot motion. It also permits operation that is more economic, flexible and lean. Some attributes of SafeMove follow [17]:

- **Increase man-machine collaboration**: SafeMove permit operators and robots to work together more closely, without compromising safety. It uses geometrical and speed restrictions to maintain automatic operation, combining the flexibility of human interaction with the precision and handling capacity of robots.
- **Reduce space in robot cell design**: SafeMove reduces the required floor space by restricting robot motion to what is needed for the application and, in some cases, adding speed limitations.
- **Reduce costs of safety devices**: SafeMove reduces the need for many safety devices, such as light curtains, safety relays, mechanical position switches and protective barriers, which can in turn reduce installation and maintenance costs.

SafeMove also incorporates electronic position switches, programmable safe zones, safe speed limits, safe standstill positions and an automatic brake test, which allow more flexible safety setups. Programmable safe zones ensure that the robot stays out of protective, three-dimensional zones, which can have complex shapes depending on the installation. Alternatively, the robot can be confined within three-dimensional geometric spaces, reducing robot installation size and floor space and permitting fences to be moved closer to the robot [18].

Some examples of SafeMove applications follow:

SafeMove example 1: Monitor and increase safety of tool zones

Consider a space with three Numerical Control (NC) machines where the operator can enter any of them to access the tool magazine, as shown in Fig. 24. When doing so, a light beam is activated to stop the operator from entering the rest of the cell. The robot is restricted by SafeMove so that it does not enter the zone with the operator, permitting 2/3 of the cell to keep operating while 1/3 is being serviced [12].



Fig. 24 - Tool zones

SafeMove example 2: Safe stand still/direct loading of a robot

An important application is the use of a robot as a direct loading device or in directly robot-controlled turntable stations. SafeMove avoids the need to power off the drives during automatic operation and regain time for starting a movement is short relative to opening relays. SafeMove has two types of functions: the passive function, where the robot monitors its state regardless of whether or not it is standing still, and the active function in which the robot is actively supervised through an input activation. Fig. 25 shows a direct loading cycle with safe stand still supervision initiated by a laser scanner.



Fig. 25 - Safe stand still/direct loading of a robot [12, 18]

SafeMove example 3: Safe axis ranges with track motions

Track motions are often associated with the need for safe zones due to the physical extension of a track and/or the use of multiple work/loading/unloading stations. In principle, tracks can also be dealt with by an Electronic Position Switch (EPS), but SafeMove allows connection to the serial measurement board (to which most tracks are connected), and an increased number of zones. In this example (Fig. 26), zones are constructed out of a combination of axes 1 and 7. When a truck is loading/unloading a specific station, axis 1 is prevented from going to the loading side if axis 7 is within the loading zone reserved by the truck [12].



Fig. 26 - Safe axis ranges with track motions

SafeMove example 4: Safe tool supervision during water jet cutting with safe-orient supervision

In processes like water jet or laser cutting, cabins are required and normally have to be built while preventing the risk that the beam cuts through it. This risk can be avoided with SafeMove. In addition to a Cartesian supervision of the Tool Centre Point (TCP), the tool orientation can be supervised, as shown in Fig. 27. Here one can select two angles to limit the orientation around the TCP. The simplest way to configure it is to move the default position of the process tool to the part, read the default reference orientation from the SafeMove configurator, and add the allowed orientation tolerance around this starting point [12].



Fig. 27 - Supervised orientation of a water jet gun

6 Robot safety standards

6.1 Technology and standardization development overview

To ensure safety in the workplace, much effort has been expended, especially in the United States and Europe, to codify the safety requirements for humans working around industrial robots. In the U.S., the Robotic Industries Association (RIA) developed the R15.06 robot safety standard through the American National Standards Institute (ANSI). In Europe, ISO brought forth the first edition of ISO 10218 in 1992, which was subsequently adopted by the European Committee for Standardization (CEN) as EN 775. The American documents provide more detailed information for the integration and use of the robots, while the ISO documents place more emphasis on requirements for robot manufacturers.

Safety requirements also evolved over time with the issuance of ANSI/RIA R15.06-1992 and the ISO10218:1992 (EN 775). While similar in scope (industrial robot safety), each standard addresses personnel safety in a different context.

An overview of robot technology development and its standardization is shown in Fig. 28.



Fig. 28 - Overview of the development of robot technology and its standardization [19]

ISO 10218 (parts 1 and 2) is intended as a harmonized standard in the European Union, and has been officially recognized in other countries as their national standards.

Work is ongoing in the US and Canada to produce an integrally combined document, as ANSI/RIA R15.06 or CAN/CSA Z434 respectively, which also contains the ISO 10218 series of standards.

An overview of the present status of robot safety standards is given in Table 1.

Type of safety standard	Europe	North America
Robot safety standard	ISO 10218-1:2011 (robot) ISO 10218-2:2011 (robot systems and integration)	ANSI/RIA R15.06 / ANSI/RIA/ISO 10218 / RIA TR R15.206 CAN/CSA-Z434-03 (R2013) (robots and robot systems)
Machinery safety standard	ISO 12100:2010 (risk assessment) ISO 13849-1:2006 (functional safety) IEC 62061:2005 (functional safety)	CSA-Z432-04 (R2009) ANSI B11.0-2011

Table 1. Present status of safety standards for robots in Europe and North America

[19]

The new ISO standards (ISO 10218) for industrial robot safety are leading documents enabling the safe use of new technologies and capabilities of new industrial robots.

6.2 Current standards for robotic safety

Various types of safety regulations apply to robot systems. Today, three different standards for robot safety are used:

Standard ANSI/RIA R15.06 / ANSI/RIA/ISO 10218 / RIA TR R15.206

The ANSI/RIA R15.06 / ANSI/RIA/ISO 10218 / RIA TR R15.206 - Industrial Robots Safety Package provides the fundamentals for industrial robots and systems, as it pertains to the safety requirements. The safety requirements are applicable to manufacturers, integrators, installers and personnel. This industrial robots safety package includes:

- ANSI/RIA R15.06-2012
- ANSI/RIA/ISO 10218-1-2007
- RIA TR R15.206-2008

Standard CAN/CSA-Z434-03 (R2013)

This safety standard applies to the manufacture, remanufacture, rebuild, installation, safeguarding, maintenance and repair, testing and start-up, and personnel training requirements for industrial robots and robot systems. It was published on 2003-02-01 and reaffirmed on 2013-05-09, and it supersedes standard CAN/CSA-Z434-94,

Standards ISO 10218-1:2011 and ISO 10218-2:2011

The ISO 10218-1 standard for the robot, and the ISO 10218-2 standard for robot systems and integration, were both published 1 July 2011. ISO 10218-1 was adopted as an ANSI standard. New features in ISO 10218 (not available before) include:

- Cableless pendants wireless operation
- Collaborative robots
- Simultaneous motion control
- Synchronous robots

In the United States, ISO 10218 and ANSI RIA 15.06.1999 are both valid. These standards are voluntary, and they provide the integrator and the robot supplier with practical advice on how a setup should be performed in a safe way. For instance, by fulfilling the requirements of ISO 10218, an installation will also fulfill the machinery directive. In other countries, only local bodies exist for the inspection of machine safety and the integration of machines. Standards such as ANSI should be used as a guideline for machine integration.

The Robotic Industries Association (RIA) and the Canadian Standards Association now are cooperating to publish a single harmonized standard for the United States and Canada. The new standard—ANSI/RIA R15.06 in the United States and CAN/CSA Z434 in Canada—will be a "four-in-one" document that includes ISO 10218-1:2011, ISO 10218-2:2011, and the unique requirements of both countries [20].

References

- [1] B. S. Dhillon. "Robot safety analysis methods", in Proceedings of the 11th National Conference on Machines and Mechanics. Delhi, India, pp. 86-93, 2003.
- [2] ANSI/RIA R15.06-1999, American National Standard for Industrial Robots and Robot Systems—Safety Requirements, American National Standards Institute, Inc. 1999.
- [3] R. Pielke Jr, how leading economists misunderstand productivity and jobs, in: The Breakthrough, <u>http://thebreakthrough.org/index.php/voices/roger-pielke-jr/its-not-about-the-ma</u> <u>chines/</u>. Accessed October, 2013.
- [4] http://commons.wikimedia.org/wiki/File:KUKA_Industrial_Robots_IR.jpg. From Wikimedia Commons, the free media repository, Accessed October 2013.
- [5] http://hopetotheend.com/robots.html. ROBOTS, Accessed October 2013.
- [6] J. E. Speich and J. Rosen, Medical Robotics, in: Encyclopedia of Biomaterials and Biomedical Engineering, Marcel Dekker, 2004, pp. 983-993.
- [7] Types of Robots, in: Loop Technology, Robotics, http://www.looptechnology.com/robotic-robot-types.asp. Accessed October 2013.
- [8] Industrial robots and robot system safety, in: OSHA Technical Manual (OTM), Section IV: Chapter 4, Occupational Safety & Health Administration (OSHA), U.S. Department of Labor, Washington, DC. https://www.osha.gov/dts/osta/otm/otm_iv/otm_iv_4.html. Accessed August 2013.
- [9] M. Alvarez, working safely around industrial robots, in: Gateway for Safety & Health Information Resources, http://www.osh.net/articles/archive/osh_basics_2002_may24.htm. Accessed August 2013.
- [10] A. Marty, T. Retsch and G. Schmitter, Safety principles for industrial robots, in: 58. Safety Applications, Encyclopedia of Occupational Health and Safety, International Labor Organization, Geneva, 2011. http://www.ilo.org/oshenc/part-viii/safety-applications/item/972-safety-principle s-for-industrial-robots?tmpl=component&print=1. Accessed August 2013.
- [11] S. Kelly, Robot safety begins with the design process, in: Robotics Online. http://www.robotics.org/content-detail.cfm/Industrial-Robotics-Featured-Articles /Robot-Safety-Begins-with-the-Design-Process/content_id/1120. Accessed August 2013.
- [12] K. Behnisch. White paper: Safe collaboration with ABB robots electronic position switch and SafeMove, 2008.

- [13] Robot Safety, in: Loop Technology, Robotics. http://www.looptechnology.com/robotic-robot-safety.asp. Accessed October, 2013.
- [14] Guidelines for Robotics Safety, in: Occupational Safety & Health Administration (OSHA), U.S. Department of Labor, Washington, DC. https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTI VES&p_id=1703. Accessed August 2013.
- [15] K. Okada, I. Maeda and Y. Sugano. "Risk assessment of robot cell production system that achieved high productivity and safety in HMI environment," Proc. of Int. Conf. on Safety of Industrial Automated Systems, pp. 181–186, Tokyo, Japan, 2007.
- [16] Robot Safety, in: RobotWorx, http://www.robots.com/articles/viewing/robot-safety. Accessed August 2013.
- [17] SafeMove Next generation in robot safety, in: ABB, http://www.abb.com/product/seitp327/ec6cfad87f69dd2dc12572d300775f5b.asp x. Accessed August, 2013.
- [18] S. Kock, J. Bredahl and P. J. Eriksson. Taming the robot Better safety without higher fences. ABB Review 4, 2006.
- [19] J. Fryman and B. Matthias. Safety of industrial robots: from conventional to collaborative applications. Proceedings of ROBOTIK 2012; 7th German Conference on Robotics, Munich, Germany, pp. 51-55, 2012.
- [20] Changes coming in the new industrial robot safety standard, in: Precision Metalforming Association, http://www.metalformingmagazine.com/enterprise-zones/article.asp?aid=6417. Accessed November, 2013.
- [21] ISO 10218 "Robots and robotic devices safety requirements for industrial robots", with parts 1 ("Robots") and 2 ("Robot systems and integration"), International standard for robot safety, Geneva, 2011.