Safety of Industrial Robots: From Conventional to Collaborative Applications

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Bjoern Matthias
ABB Germany

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Jeff Fryman, Robotic Industries Association, Ann Arbor MI, USA
Björn Matthias, ABB Corporate Research, Ladenburg, Germany

Summary / Abstract

Industrial robots, previously completely separated from human access when in operation in the factory, are acquiring control capabilities rendering them capable of conforming to new forms of operation, with suitably controlled risks to allow human workers access to the robot work space during operation. We survey the developments of industrial robots and of the robot safety standards, outlining the steps that have brought us to the present status, the opening of possibilities for human-robot collaboration in industrial production. The four basic types of collaborative operation are summarized and open research questions in this area are formulated.

1 Introduction

Industrial robots have been used increasingly in production for over five decades in widely varying applications, ranging from spot welding in the manufacturing in automobiles to the pick-and-place operations in the packaging industry. The successful deployment of presently over one million industrial robots has rested traditionally on a number of factors: on repeatability as a tool to achieve consistent quality, on the speed and force they make available to manufacturing processes, on the flexibility brought about by programmability, on the possibility to delegate hazardous production tasks to machines to a greater extent, and also on the reduction of the manufacturing work force. But since the installation and commissioning of robot applications is still today associated with appreciable effort and cost, the underlying assumption in their large-scale deployment in production environments still rests on the economy of scale brought about by large product lot sizes and a comparatively rare need for retooling or changeover. In addition, since robots as a rule are hazardous machines that require safeguarding against human intervention, investments in protective guards and safety equipment are non-negligible. The floor space use of a fenced robot installation is also associated with increasing costs for real estate.

Recent years have seen a rather rapid development of more complex safety functionality for industrial robots, driven from the technological side by advances in microprocessors and safety-certifiable components on all levels. The business opportunity this addresses aims at introducing robots into new application environments, in which the traditional business paradigm does not hold. In order to reduce the need for floor space and for conventional safeguarding while maintaining advantages of robotic automation associated with quality and increasing flexibility further, robots must be enhanced to be able to operate in closer quarters with human workers in the production environment. While the approach of human-robot collaboration (HRC) in industrial production is only now beginning to make its way into practical applications, the relevant expert communities have been very active in the development of the related functionality, of the required safety capabilities residing increasingly in sensors and processors, and in the standardized documentation of the requirements to be fulfilled by industrial robots and robot systems.

2 Historical Overview of Industrial Robots and Safety Requirements

Robots play an extremely important role in our society today. Nowhere is that more visible than in manufacturing and the industrial environment on a world-wide scale. Worker productivity and corporate competitiveness are key elements in a healthy economy, and both are enhanced by the use of industrial automation and robots. This is obvious by the number of robots in use today – an estimated 1.3 million units worldwide – as reported by the International Federation of Robotics statistical analysis [1].

Even as the numbers increase, industrial robots continue to evolve to the benefit of workers around the world, both in productivity and safety. Since the very beginning of the robotics industry, safety has been an extremely important concern; and a success story for the industry. The early hydraulically powered industrial robots caused much concern for safety, and this concern was warranted. These robots were large and powerful, with huge mechanical advantage compared to other devices of the time. The controls were simple, and not truly reliable. While the early robot manufacturers were justifiably pleased with the technology advances in automation that these machines brought to industry, the concern for the safety of humans working around these machines led to the obvious conclusion – cage them off from the world and do not let anyone near to them. This, of course, was a successful solution, and safety was achieved – at least for normal operations that did not require human intervention.

The early robots did much to remove humans from hazardous, tough and dirty jobs in the factory. The workers' life was much improved and the working conditions around the factory improved. Examples include foundry, forging and stamping tasks. To ensure safety in the workplace, work was started in the United States and in Europe to codify the safety requirements for humans working around industrial robots. In the USA, 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 CEN as EN 775.

Robot technology development continued, and newer, more capable electric drive robots with servo controls greatly expanded the use of industrial robots in the work place. While still not as reliable from a safety standpoint to the extent today' robots are, these new technologically advanced machines went on to transform many more industrial jobs that required more precision and repeatability, most notably in welding applications, both spot and arc. For many years, welding accounted for virtually half of all robot applications; and welding continues today as a leading use of industrial robots.

Safety requirements also evolved over time with the issuance of ANSI/RIA R15.06-1992 and the ISO 10218:1992 (EN 775). While similar in scope – industrial robot safety – these two documents did not address personnel safety in the same context, with the USA document providing more detailed information for the integration and use of robots while the ISO document gave more emphasis on requirements to the manufacturers of robots. An overview of the development of technology as well as of the standardization is given in **Figure 1**.

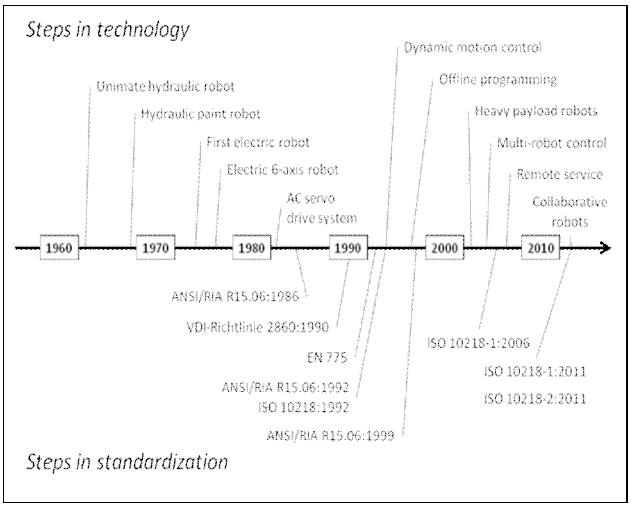

Figure 1 History of industrial robots and their safety standardization

The prevailing safety concept of locking the robot out of reach of the humans continued, though much more thought was given to the need for humans to interact with the robots, particularly as maintenance interventions and setting were needed. Much additional thought was given to the enhancement of proper control and operation of the robots and the selection of the proper safeguarding.

Because each robot installation is unique from its application, location, and operation, it became generally understood that risk assessment, particularly a structured risk assessment, was needed to properly assess the levels of harm possible in a designed system. The importance of understanding both the task and the hazard associated with that task led to the suggested task-based risk assessment methodology introduced in the ANSI/RIA R15.06-1999.

Robot technology continues to evolve, but after the turn of the century so many new elements of robot control had been introduced that it was obviously time to evolve the safety standards to recognize the improvements and provide new and better guidance for the human interaction with industrial robots. Work was begun to evolve the ANSI/RIA R15.06-1999 from the USA into the ISO 10218 standards arena. Thus the work on a truly global standard for robot safety was born.

The fruits of this work, carried out under the auspices of the ISO TC184/SC2 WG3 for Industrial Robots [2], first resulted in the publication in 2006 of ISO 10218-1 dedicated to only the robot. This was a comprehensive document for the robot manufacturer to provide guidance in building suitable industrial robots. In addition to the many controls improvements made, recognition of even more and exciting changes for the future were facilitated. Work continued into 2011 developing safety requirements for the robot system and integration which was published in July as ISO 10218-2:2011 [3]. Simultaneously the second edition of ISO 10218-1:2011 was published so that both documents are in "sync". The ISO 10218 documents, both part 1 and part 2, have been published as harmonized standards in the European Union; and work is ongoing in other countries to officially recognize these standards as their national standards. In fact, work is ongoing in the USA 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. A tabular overview of the present status of robot safety standards is given in **Table 1**.

The new ISO standards for industrial robot safety are leading documents enabling the safe use of new technologies and capabilities of new industrial robots. The advent of new "safety-rated" software controls for the industrial robots make new applications possible and allows the introduction of new automation capabilities into new markets possible. Most notable is the advent of the "collaborative robot", where the human and the machine work in close harmony with one another. No longer is the robot "locked away" behind a fence prohibiting access, but the human is allowed inside the "fenced" area to directly share a common work space with the robot.

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

	Europe	North America
Robot safety standards	ISO 10218-1:2011 (robot) ISO 10218-2:2011 (robot systems)	ANSI/RIA R15.06-2009 CAN/CSA Z434-2008 (robots and robot systems)
Machinery safety standards	ISO 12100:2010 (risk assessment) ISO 13849-1:2006 (functional safety) IEC 62061:2005 (functional safety)	ANSI B11.0-2011
Machine safety legislation	European Machinery Directive	(no equivalent)
Workplace safety regulations	e.g. Berufsgenossenschaft directives (DE)	OSHA 1910 (US) Provincial regulations (CA)

3 Moving Humans and Robots Closer Together in the Factory

The past decade has seen growing interest in the technology for and economic relevance of bringing humans and robots closer together in the manufacturing working environment [4], [5]. As flexibility requirements continue to increase, the optimal degree of automation will often turn out to be less than 100% and the role of the human worker remains important [6], [7]. Due to their contributions to product quality and their inherent flexibility, industrial robots will also retain an important role in the manufacturing environment of the future.

The conventional deployment of industrial robots to automate manufacturing processes is seen to have its particular economic advantages over hard automation and over manual labor for a medium range of lot sizes. Softening the limits of robotic automation to allow a distribution of tasks between humans and robots introduces a new dimension into this argument and widens the applicability of robots for industrial production. In **Figure 2** we show how the introduction of HRC applications increases the area of relevance of industrial robots for automating manufacturing tasks.

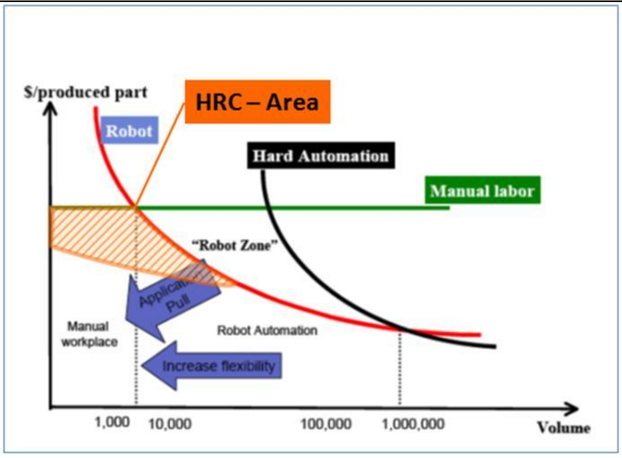

Figure 2 Introduction of HRC extends the applicability of industrial robots to a larger part of industrial production (adapted from IFR World Robotics Report, 2007).

Standard industrial robot systems pose hazards to humans due to their inertia, structure and process forces. Protection strategies, as outlined in safety standards, must be applied to assure operator safety. The present challenge is realizing the flexible manufacturing environment of the future with a mixture of human workers and robots, in essence a cooperative manufacturing setting. Here, humans and robots each take on the tasks for which they are best-suited, with frequent interaction and shared procedures. The strict temporal and spatial separation between them is lifted.

Several versions of these collaborative types of operation have been envisioned and enabling requirements are established in the ISO 10218- standard. These will be considered in a bit more detail in the following section.

4 Types of Human-Robot Collaborative Operation

Until recently, robot users interested in more close collaboration between robots and humans in their applications have found that there was little guidance for safety aspects of such installations and have, therefore, shied from exploratory work without backing in standards. With the recent revision of the standard ISO 10218 [3], explicit consideration has been paid to the needs of users wishing to deploy human-robot collaboration (HRC) in their applications. While the tried and proven basic safety functionality of industrial robots remains relevant and present in the text of the standard, the new functions associated with HRC are not at this time based on extensive practical use. This situation is unlike the typical situation of standardization projects, in which groups of experts consolidate the known body of best practices. In the case of

HRC, the standardization effort for safety is in effect a close cooperation between technical experts in industry, academia and research organizations aiming to develop simultaneously the body of knowledge governing the safety aspects of HRC as well as documenting this also in the text of standards documents.

The two parts of ISO 10218 presently give a very brief description of basic safety requirements for four basic types of collaborative operation. More details will become available in a future document, the technical specification ISO/TS 15066 [8], which is presently under development in the committee ISO/TC 184/SC 2/WG 3 [2]. The objective is to bring forth a document with quantitative guidance in the area of human-robot collaborative applications.

These applications can be classified in various ways, but any such classification rests on the observation that there will be a portion of the work space in the cell that is accessible both to the robot and to the human in a physically unobstructed way. This volume is called the "collaborative work space" (CWS). For the purposes of standardization, the possible basic types of collaborative operation have been chosen to reflect a number of fundamentally different methods to reduce risk when human and robots work together closely. These basic types of collaborative operation, using the titles of the sections in the standardization documents, together with the main measure for risk reduction for each case, are:

- **Safety-rated monitored stop**
  While the worker is in the CWS, the robot is not permitted to move. Rather it must hold its position, even if its drives are still energized.
- **Hand guiding**
  Here, the worker has direct control of the robot. Motion is only possible when the worker purposefully activates an input device to cause the desired motion. The robot speed must be limited to a value obtained by risk assessment.
- **Speed and separation monitoring**
  Contact between the moving robot and the human worker is prevented by supervising the worker's position and adapting speed and/or position of the robot to maintain this condition.
- **Power and force limiting**
  Contact between the robot and the human worker is considered possible as a normal event during the application, but the nature of these contacts is controlled by inherent design measures of the robot and/or by measures of safety-rated control. In either case, the objective is to limit static and transient forces that the robot is able to impart to exposed parts of the worker's body.

Realistic applications can consist of combinations of these methods. Practical applications of human-robot collaboration may, therefore, require that the motion of the robot manipulator be supervised, as is possible today with many safety controller options available with commercial robot controllers.

In addition, however, there are capabilities that are presently under development. These include sensory capabilities providing safety-related information on the position of the human worker and reliable predictions of braking distances in real-time when worker and robot interact in the same workspace, but should not come into direct contact.

Furthermore, when physical interaction is included in the application, especially stringent requirements hold on the nature of this contact. This may be the most challenging of the new methods for operation, since contact is no longer a taboo. It is possible, may be part of the application, and must therefore be understood and controlled. This is a change of paradigm compared to the applications of conventional industrial robots that will lead to the development of new types of robot control as well as to new types of robot manipulators.

Significant research effort is being invested into the study of the different relevant thresholds that must be invoked in a full understanding of low-level mechanical loading of the human body [9], [10], [11]. Efforts range from modeling the dynamics involved, not just of the robot, but also of the human body, to deriving practically usable limit criteria that can be followed when designing robots and applications. The underlying biomechanical data is, however, still very scant.

As yet unpublished work is ongoing at the University of Mainz and elsewhere to establish the thresholds delimiting touch sensations from pain sensations in various zones of the body. Thresholds for injuries as such cannot be investigated directly, but must be inferred [12] from other studies published in the medical literature. A simplified schematic of the hierarchy of these thresholds is shown in **Figure 3**.

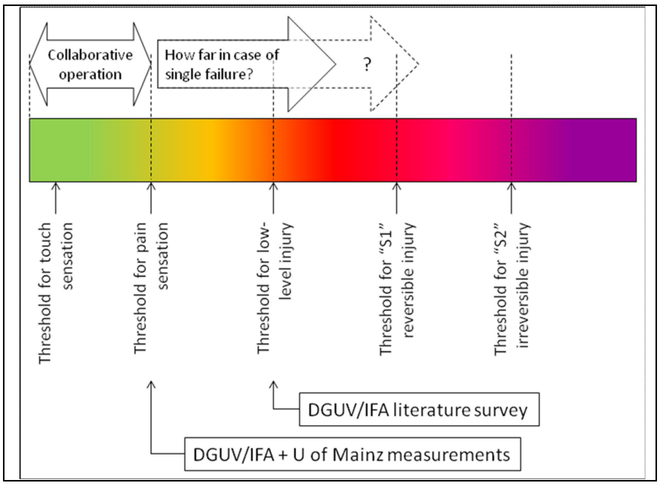

Figure 3 Overview of various thresholds relevant for describing contact events between robots and humans

5 Conclusions and Outlook

While the “simpler” types of human-robot collaborative operation by way of a safety-rated monitored stop or by hand guiding can be realized with present day technology, the full implementation of the other two types are still pending additional research results and product development.

Maintaining a specified separation distance between any part of the moving robot and the worker means that the control system must at all times have information not only on the pose and motion state of the robot, but also on the position and anticipated motion of the worker, as long as he is in the CWS. To date, sensors suitable for use in safety-rated systems are limited to delivering binary information on the presence of an object in one or more statically defined regions in space (zones). One may anticipate, however, that safety sensors will become available with the capability of delivering safety-rated position information on objects detected in their field of view.

Finally, the proper limiting of both static and dynamic forces that a collaborative robot shall be able to impart to exposed parts of the worker’s body requires fundamental understanding of the biomechanical mechanisms involved and how they correlate to the dynamical properties of robot motion and to the specifics of the affected body part.

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7 References

[1] World Robotics – Industrial Robots: Statistics, Market Analysis, Forecasts, Case Studies and Profitability of Robot Investment, International Federation of Robotics, Frankfurt am Main, 2011.

[2] ISO/TC 184/SC 2 “Robots and robotic devices”; working group WG3 “Industrial safety” is one of five active working groups in this subcommittee. See committee web site: http://www.iso.org/iso/iso_technical_committee.html?commid=54138

[3] ISO 10218 “Robots and robotic devices – Safety requirements for industrial robots”, with parts 1 (“Robots”) and 2 (“Robot systems and integration”), ISO Copyright Office, Geneva, 2011.

[4] M. Hägele, W. Schaaf, and E. Helms, “Robot assistants at manual workplaces: Effective co-operation and safety aspects,” In: International Symposium on Robotics ISR 2002 / CD-ROM: Proceedings. October 7-11, 2002, Stockholm, Sweden. Stockholm, 2002.

[5] A. De Santis, B. Siciliano, A. De Luca, and A. Bicchi, “Atlas of physical human-robot interaction,” Mechanism and Machine Theory, Vol. 43, No. 3, March 2008, p. 253-270.

[6] J. Krüger, T. K. Lien, and A. Verl, “Cooperation of human and machines in assembly lines,” in: CIRP Annals Manufacturing Technology. 58 (2009), No. 2, p. 628-646.

[7] R. D. Schraft, M. Hägele, and A. Breckweg, “Man and robot without separating systems,” In: World of Automation and Metalworking. Frankfurt/M.: VDMA Verlag, 2006, p. 4-5.

[8] ISO/TS 15066 “Robots and robotic devices – Industrial safety requirements – Collaborative industrial robots”; ongoing standardization project in draft stage and not publicly available at this time.

[9] S. Haddadin, A. Albu-Schäffer, and G. Hirzinger, “Soft-Tissue Injury in Robotics,” IEEE / Robotics and Automation Society, 2010 IEEE International Conference on Robotics and Automation, Anchorage, Alaska USA, 2010, on DOI - 10.1109/ROBOT.2010.5509854, p. 3426-3433.

[10] O. Ogorodnikova, “How Safe the Human-Robot Coexistence Is? Theoretical Presentation,” Acta Polytechnica Hungarica, Vol. 6, No.4, p. 51-74 (2009).

[11] S. Oberer, R. D. Schraft, “Robot-dummy crash tests for robot safety assessment,” IEEE / Robotics and Automation Society: 2007 IEEE International Conference on Robotics and Automation, Rome, Italy, 2007, p. 2934-2939.

[12] BG/BGIA Risk Assessment Recommendations according to Machinery Directive – Design of Workplaces with Collaborative Robots, Ed. BGIA – Institute for Occupational Safety and Health of the German Social Accident Insurance, U 001/2009e October 2009 edition, revised February 2011. http://www.dguv.de/ifa/en/pra/kollaborierende_roboter/index.jsp