Secure Human-Robot Collaboration (HRC)

PILZ
THE SPIRIT OF SAFETY

White paper

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1. Edition

At a glance

For safety reasons, humans and robots have been going their physically separate ways for years now. Today, productivity increases as well as demographic change with an increasingly aging working population are an impetus to tap into the potential of human-robot collaboration (HRC). If, however, humans and robots want to share a workspace, then the subject of safety is of central importance. The requirements in relation to safety technology always depend on the respective application. Safe robot cells only come about when everything is taken into consideration – standards, robots, tools and workpieces as well as the associated machines such as materials-handling technology. In practice, this means that each application requires its own separate safety-related review.

This white paper sets out challenges and possible solutions in the implementation of safe human-robot collaboration in industrial settings.

Contents

1. Fascination with robots

There is hardly any other machine that catches the imagination of humans as much as robots. They are considered to be the perfection of machines due their larger degree of freedom in terms of diversity and the scope of their activities. Robots ultimately express the human aspiration to have machines that participate in people’s lives and assist them in every situation.

1.1. Robots in the 20th century

The term “robot” itself was coined in the 20th century. It originates from the Czech term “Robota”, which in that language stands for “forced labor” or “drudgery”. The Czech author Karel Čapek published a play in 1921 about a company that manufactures artificial humans. This is where the term robot was used for the first time in connection with machines.

It also triggered an increasingly critical analysis of machines that act autonomously. The central question was: How can the safety and security of humans and machines be ensured when humans and machines are working closely with one another? In 1942, the Russian-American scientist and science-fiction author Isaac Asimov described the “Laws of robotics” in a short story. These read as follows:

1. A robot may not injure a human being,
2. A robot must obey,
3. A robot must protect its own existence (unless this contravenes Law 1 or 2).

1.2. Robots in the industrial environment

Industrial robots are an invention from the second half of the 20th century. The American George Devol heralded in this era in the Fifties with his patent design for “programmed article transfer.” In 1961, a robot, Unimate, was used for the first time at General Motors.

To ensure that workers were protected, a strict separation of humans and machines was enforced. The robot was supposed to replace human labor and remained housed in a cell to complete its tasks. Separate workspaces and no direct interaction between humans and machines: These principles remained unchanged for over 50 years. These robot applications did not chime with the idea of humans and robots collaborating closely with one another.

Today, robots are deployed in many different ways. They are not only to be found in the industrial environment, but also play an increasingly important role in the areas of research and medicine. Different robot types can be differentiated for the various application areas. In the industrial environment, industrial robots are key to supporting humans and machines in their work.

1.3. Difference between service robots and industrial robots

Service robots and industrial robots differ in several aspects.

ISO 8373 defines an industrial robot as an automatically controlled, reprogrammable multipurpose manipulator programmable in three or more axes for use in automation technology either in a fixed location or arranged such that it can move. In accordance with ISO 8373, an industrial robot comprises the manipulator (robot arm), including drives; the controller, including control unit and any communication interface (hardware and software).

In the industrial sphere, a distinction is also made between a robot system, robot cell and robot line:
The system comprises the industrial robot, end effector as well as all machines, equipment, devices, external auxiliary axes or sensors that support robots to fulfill their tasks. A robot cell comprises one or more robot systems plus the associated machines and equipment, as well as the associated protected area and protective measures. Finally, an industrial robot line comprises several robot cells, including the associated machines and equipment, as well as the associated protected area and protective measures.

Service robots, on the other hand, are robots that carry out useful tasks for humans or devices, not taking into consideration automated applications in the industrial environment. As the name already suggests, service robots carry out services for humans. These include, for example, household robots or personal mobility assistants for the private domain or delivery robots in offices and hospitals, and robotic firefighters.

1.4. The market for industrial robots

The market for industrial robots is growing constantly: In 2015, this market achieved a record increase of 12% worldwide, of which 16% in Asia, 10% in Europe and 15% in North America. In 2018, around 2.3 million robot systems will be used.
However, experts currently estimate the market for service robots to be smaller: In 2015, only 5% of robots sold worldwide were service robots. However, according to experts, this trend will also change: The expected growth rate in the years 2016 to 2022 is 60%, which means an increase to 3.3 billion U.S. dollars.

2. From cooperation to collaboration

Closer collaboration between humans and machines is to be possible due to a new type of robot called a cobot. The name cobot comes from combining the words “collaboration” and “robot” and describes robots that were designed for direct interaction with humans. In human-robot collaboration (HRC), humans and robots share a workspace. The strengths and advantages of the machines such as reliability, endurance and repetition accuracy are therefore combined with the strengths of humans, i.e. skill, flexibility and decision-making ability. In human-robot collaborations such as these, the workspaces of the humans and robots overlap spatially and temporally. Typical areas where they are deployed are “pick and place” applications (handling between various production steps) or “follow the line” applications where the robot must exactly execute a predefined movement path (e.g. when retracing a contour or for gluing work).

2.1. Standards

Robots are incomplete machines within the meaning of the Machinery Directive 2006/42/EC. Detailed safety requirements are available in the form or the two standards ISO 10218 “Safety of Industrial Robots” Part 1: “Robots” and Part 2: “Robot systems and integration”.
These standards do not apply to robots outside of the industrial sector.

The German versions of both parts are published as EN ISO 10218-1:2011 and EN ISO 10218-2:2011 and listed as harmonized C standards under the Machinery Directive 2006/42/EC. These international standards were drawn up taking into account the specific hazards arising from industrial robots and industrial robot systems. Information on collaborative operation is also to be found in Part 2 “Robot systems and integration”.
When planning a HRC application, the choice of robot is a key point for the systems integrator. EN ISO 10218-1 also contains safe drive functions. In accordance with EN 61800-5-2 (Adjustable speed electrical power drive systems – Part 5-2: Safety requirements – Functions), these include, for example: Safe Operating Stop (SOS), Safely-Limited Speed (SLS), Safe Speed Range (SSR) and Safely-Limited Torque (SLT).
The requirements for “safety-related parts of the controller” (electrics, hydraulics, pneumatics and software) are clearly defined in chapter 5.2 of EN ISO10218-2 Robot systems and integration. The safety-related parts of the controller must be designed in such a way that they comply with PLd in category 3 (ISO 13849-1:2006) or SIL2 with a fault tolerance and an MTTF of at least 20 years (IEC 62061:2005).

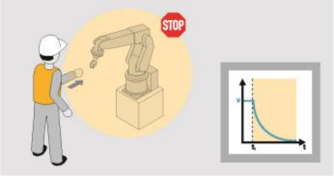
2.2. New safety requirements

HRC applications are setting new requirements when it comes to safety. The main distinguishing feature between “traditional” housed robot applications and HRC is that collisions between machines and humans could be a real scenario. However, these must not lead to injuries. On the one hand, more reliable controllers and intelligent, dynamic sensors on the robot itself are prerequisites for the coexistence of humans and robots in an injury-free manner. The robot therefore senses a collision when or before it occurs. On the other hand, reliable safety standards must be set on a normative basis.

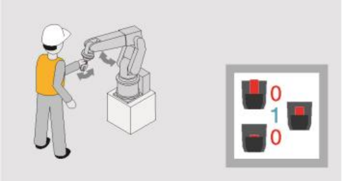
In practice, however, existing standards proved to be inadequate to safely implement an actual collaboration between humans and machines in which the respective workspaces could overlap in terms of time and space. There was a normative gap that could only be closed off in spring 2016 with the publication of the technical specification ISO/TS 15066 “Robots and Robotic Devices - Collaborative industrial robots”. On the one hand, four collaboration types are now described in more detail in the document as protection principles. On the other hand, there now also exists detailed information on pain thresholds for various regions of the body. Like all technical specifications, this specification is an international standard that is implemented nationally.

HRC requires protective measures so that the safety of humans is guaranteed at all times during the collaborative operation. For this purpose, four collaboration types are described in greater detail in ISO/TS15066 as protection principles. Safe HRC requires, on the one hand, robot systems that are specially designed for the respective collaboration type. Risk minimization can be implemented by applying the collaboration types described below:

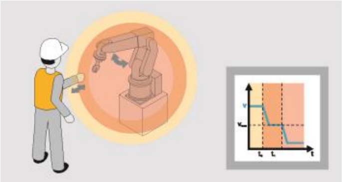
- Safety-rate monitored stop (method 1): The human only has access to the robot when it is at a standstill. A collision is therefore excluded.



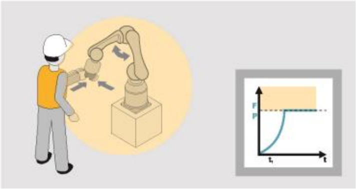
- Hand guiding operation (method 2): The human only has access to the robot when it is at a standstill, the human guides the robot manually. A collision is therefore excluded.



- Speed and separation monitoring (method 3): The human has access to the collaborative space during operation. The human’s safety is ensured by the distance from the robot. If the distance is too short, a safety stop is triggered. A collision is therefore excluded.



- Power and force limiting (method 4): In this method, the human also has access to the collaborative space while the robot is moving. Contact between humans and robots (whether intentional or not) is possible!



When implementing safe human-robot collaboration, the systems integrator can chose one or a combination of these “collaboration types” for his application. In practice, it is shown that human-robot collaborations can often be efficiently implemented under ISO/TS15066 by combining “speed and separation monitoring” with “power and force limiting”. However, if collisions are a possible scenario, it must nevertheless be ensured that the contact does not lead to injury.

For the first time, the technical specifications provide detailed information in Annex A on pain thresholds for various parts of the body. These values form the basis for being able to implement an application without a safety fence, i.e. one that follows method 4.

As a member of this international standards body, Pilz has actively collaborated with robot manufacturers, integrators, notified bodies (such as BG) and other automation companies on the design of this pioneering technical specification for human-machine collaboration in the industrial environment..

However, there are definitely robot applications that will continue to need a safety fence. This is the case, for example, when there are very pointed or sharp-edged tools or workpieces or when high forces and speeds are required for the process.

3. Sensor technology kit for safe robots

Safe sensor technology plays a key role in the technical implementation of robot applications: A sensor kit is necessary to meet the safety requirements for all applications.

3.1. Sensors for safe access to robot cells

When humans and robots share a common workspace, efforts are made to support the safety of the application using safety components and functions in or on the robot. For example, safe movement functions in the robot are combined with near-field sensors, with integrated torque monitoring in the robot or with a tactile sensor technology that envelops the robot. While tactile sensors register contact, capacitive, i.e. contactless, sensors, can detect a collision before it occurs. The movements for this type of robot application are generally significantly slower than in fully automated applications.

If human intervention in the production process is generally not necessary or is not desirable, machines and systems are surrounded by protective devices that mechanically separate them off. For robot cells of this type, it generally applies that they must only be entered for service purposes. Safety gates are suitable for this access and they, in turn, must be secured with safety gate sensors: If a safety gate is opened, the sensor detects this and generates a shutdown signal for safe machine control.

Various actuation principles and designs are used, depending on the requirements, installation situation and applicable basic conditions: Contactless safety magnetic sensors are a very economical solution for concealed installation while safety RFID-based sensors, such as the PSENcode safety switch, allow maximum freedom during mounting and the highest degree of manipulation protection.

If, due to space constraints, protective devices must be placed near a hazardous movement, there is a risk of hazardous overrun. In this case, it is absolutely necessary to use a safety locking device. Mechanical locking devices with spring locking such as PSENmech or integrated safety gate systems such as PSENsgate, PSENmlock and PSENslock carry out these tasks. There are numerous device variants available for all of these technical sensor principles, which means that virtually all conceivable monitoring scenarios can be achieved.

In the area of robot-supported automotive body shell assembly, PSENcode safety switches from Pilz are used, for example; these can monitor up to three positions with just one sensor. These are used at the interfaces between humans and robots where manual interventions are necessary, e.g. feeding and removing sheet metal parts to and from the robot cells enclosed in protective grids.

For robot applications where, for example, human monitoring, the insertion of parts or rework by humans is necessary, contactless protective devices such as safety light curtains are also used for access protection. In addition, it may be necessary to install rear area protection in the form of horizontally installed safety light curtains or a safety laser scanner. In some cases, safety mats are the preferred choice, if, for example, there are availability problems with the optical systems due to procedural conditions such as dust, fumes, mist or vapor.

3.2. Camera-based safety for HRC

For human-robot collaborations with robots with a larger load capacity, traditional safety concepts based on separating protective devices are, as already mentioned, reaching their limits – others are required. For these, a considerably more differentiated consideration of events is necessary. For example, a distinction must be made as to whether a human can stay in the potential action area of a hazardous movement (warning zone) or can already access a zone with increased safety requirements (protected zone). Ideally, it must be possible to dynamically adjust these zones and, for example, to track the safety monitored movements of the machine or robot. In this environment, human-robot collaborations can be achieved where static protective devices are reaching their limits.

New camera-based methods are capable of securely monitoring protected fields and zones in a multi-dimensional manner, such as, is achieved, for example, with the SafetyEYE 3D camera system. Due to their 3D operating principle, sensor systems such as these are opening up new possibilities in application design. In addition, protected zone requirements can be adjusted at each process step.

Further developments in this area are contingent on the requirements of the upcoming applications: a combination of a safe robot with a safe 3D camera system with more intensive communication can merge and optimize various process steps that are currently strictly separated from one another. The safe robot knows its safe position, its safe speed and its safe direction of movement, the safe camera system knows the position of objects (people) in the vicinity of the robot’s operating radius. Instead of abruptly switching off, the entire system can respond in a considerably more flexible manner, avoid unnecessary downtime and thus increase the productivity of the system. In the event of a violation of the protected zone, the robot does not have to undergo a hard stop immediately. Or to phrase it in another way: If there is no human in the robot’s operating radius, the working speed of the robot, and thus the productivity of the process, is increased thanks to SafetyEYE.

3.3. Further developments in sensor technology

Sensor technology will continue to play a key role in making robot applications safe. Pilz is involved in shaping the future with its comprehensive research and development activities.

A pressure-sensitive mat that was developed based on tactile fabric developed by Pilz is available for safety and control tasks in robotics. This tactile sensor system is based on technology developed by the Fraunhofer Institute for Factory Operation and Automation (IFF). The sensitive layer is located on the inside. It is therefore possible to integrate spatial resolution into the mat itself. This tactile sensor technology provides support for the visualization and location identification of people and is a very promising method of bringing more dynamism into HRC. The system is being further developed such that the direction of movement of objects and people can be displayed thanks to spatial resolution.

The pressure-sensitive mat detects the position and direction of movement of the person and transmits the data to the robot controller to avoid unwanted collisions between humans and machines. In addition, the position of the human is displayed as a heatmap on a monitor.

Furthermore, Pilz is presenting two compact stereo cameras (that it developed in-house) at trade shows. These are the results of the research projects Konkamis and Insero3D in which Pilz is active as a project partner. The cameras enable detection of obstacles in real time so as to avoid collisions between humans and robots. For the controller, Pilz developed software modules for the dynamic detection of obstacles, which works on the basis of the Robot-Operating-System (ROS).

The cameras are mounted on the control panel with a view of the robot application. Data is transmitted to the robot controller via a ROS node for path planning purposes. Robots can thus transport workpieces flexibly and avoid both static and moving obstacles.

Pilz is thus demonstrating that the programming environment that is familiar to date from the research environment can also be used in industrial applications.

4. Step by step for safe robot application

4.1. A risk assessment is carried out at the beginning

It must be taken into account that, in accordance with the Machinery Directive, the robot of itself is only an incomplete machine; it is only be means of grabs or the tool necessary for the respective application that the robot receives a specific purpose and must be considered a complete machine. The integrator or user thus becomes the manufacturer of the machine and is responsible for CE marking, including safety inspection.

Corresponding guiding principles for risk assessment and mitigation are defined in EN ISO 12100 Safety of machinery. The iterative process is crucial for risk assessment. This is divided into the steps of risk analysis and risk evaluation. Risk assessment involves determining the applicable harmonized standards and regulations, determining the limits of the machine, determining all of the risks within each life phase of the machine, the actual risk appraisal and assessment and the recommended approach to reduce the risk. For the risk assessment, it is important that each hazardous area is considered individually and without protective measures.

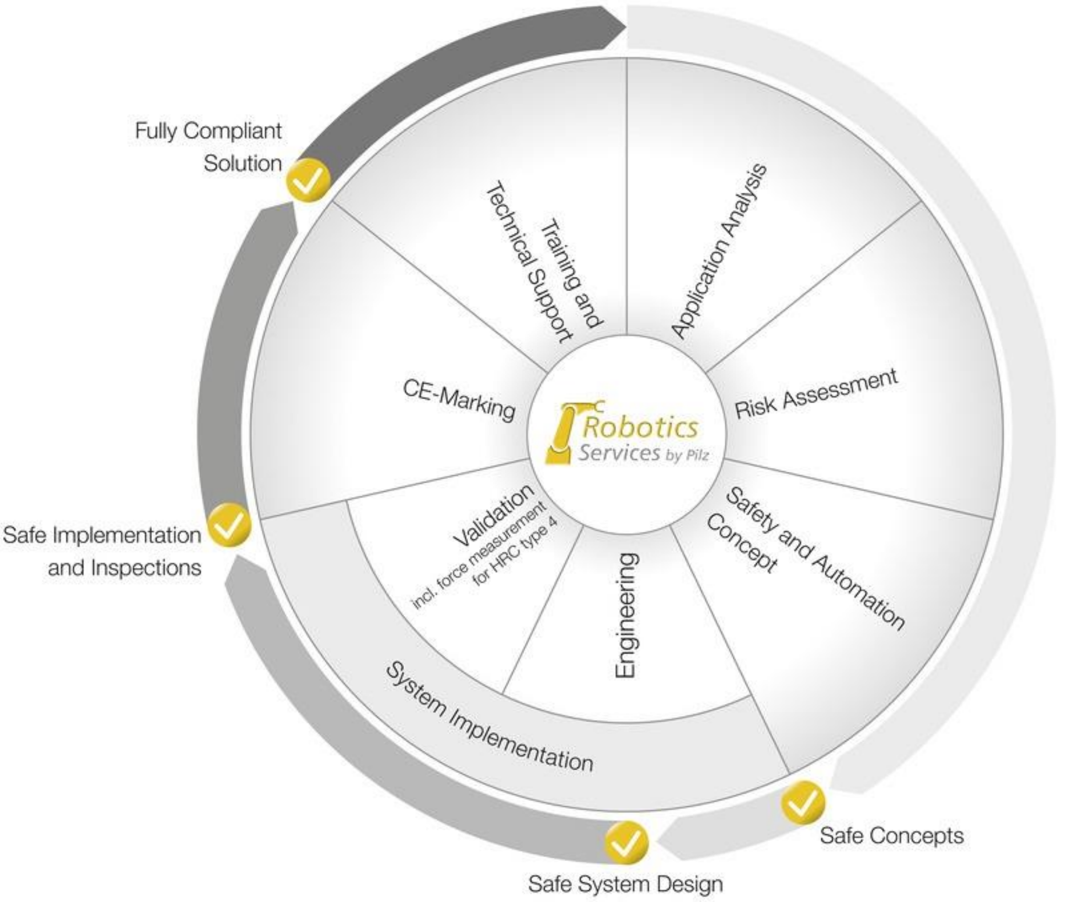
The challenge for robot applications without safety fences is that the boundaries between the working spaces of humans and machines are disappearing. In addition to the hazards posed by robots, the movements of humans must also be taken into consideration. However, these cannot always be calculated with regard to speed, reflexes or the sudden entry of additional people.

4.2. The central role of validation

The safety concept and system integration are developed in a customized way based on the risk assessment. The previous steps are reflected once again in the subsequent validation. In contrast to risk assessment, each hazardous area is taken into account with protective measures in validation. For this, the robot application must be in a state such that it is ready for delivery.

In accordance with the standard, various methods must be applied for the validation, including visual checks, practical tests and measurements. Validation includes, among other things, the verification of the required performance level PLr, a fault simulation (2-channel triggering, cross-fault, etc.), overrun traverse measuring if the HRC application is to be made safe using speed and separation monitoring, checking of the checklist in Annex G to EN ISO 10218-2 as well as collision measurement in the event of the use of the power and force limiting method. The systems integrator must validate over 200 points in total.

As a solution provider, Pilz provides supports for the implementation of relevant standards and directives. Jointly with the customer, the experts at Pilz work out a globally optimum safety strategy for robot applications along the life phases of the robot system through to CE marking. The training course with up-to-date and practical content rounds off the offer.



4.3. Touching without injuring

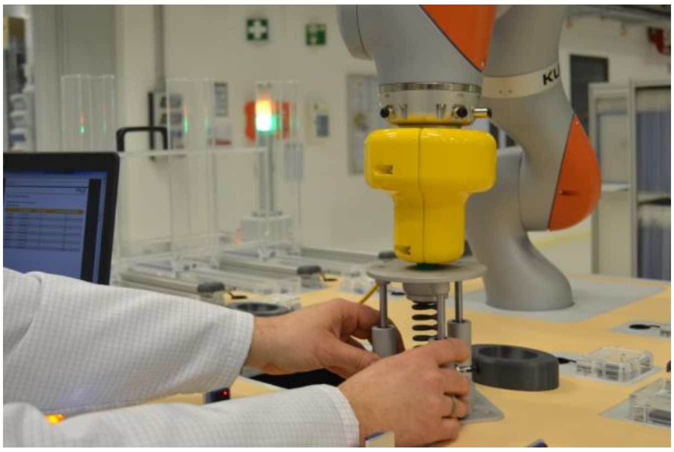
Collisions can be mitigated in various ways: Through design measures such as the rounding of edges and corners, cushioning or contact surfaces that are as large as possible so as to distribute the force over the area. Technical protective measures can also be used (e.g. reduction of the speed of the robot movements as well as adjustments to the robot path so as to avoid collisions with particularly sensitive parts of the body). Employee training can also help to reduce the risk of injury.

Finally, it must be determined by means of a measuring method whether the possible collisions are harmless from a technical safety perspective. A body model with 29 specific body areas divided into 12 body regions is provided in Annex A to technical specification ISO/TS 15066. The body zone model makes a specification regarding the respective exposure limits in terms of force and pressure for each part of the body (e.g. the head, hand, arm, or leg). The region of the body with the lowest permissible collision values is the face. A maximum force of 65 N and a pressure of 110 N/cm2 may be exerted here. If the application stays within these limits when there is an encounter between a human and a robot, then it is in compliance with the standards.

4.4. Measurement of force and pressure in accordance with ISO/TS 15066

As for all measurement methods, these types of measurements must be comprehensible, traceable and reproducible. Pilz therefore developed the HRC collision measurement set for this special force and pressure measurement.

The system, which is equipped with springs and corresponding sensor technology, measures the forces exerted on the human body exactly and compares these with the limit values in accordance with ISO/TS 15066. The measuring device for this is installed at the positions determined during the risk assessment, between the robot arm and a stiff, inflexible base. This simulates virtually static contact, e.g. a worker being crushed between the robot and the system. The measurement is then started via software and the data is then processed and documented. If the limit values are exceeded, the speed of the robot must be reduced or additional safety measures such as light grids or a separating protective device (guard) must be installed.



Besides the measuring device, slides, scanner and compression elements, the set also contains various springs that can be used to simulate the various area of the body. Pilz rents out the set, which also includes training, maintenance, calibration and regular updates.

5. Summary

To date, at least, there is no one safe robot or one safe sensor technology that covers all possible scenarios from the applications in terms of safety. The requirements in relation to the safety technology always depend on the respective application. Safe robot cells only come about when everything is taken into consideration – robots, tools and workpieces as well as the associated machines such as materials-handling technology. In practice, this means that each application requires its own separate, in-depth safety-related review. The safe HRC application is therefore ultimately the result of the interaction of normative basic conditions, a complex risk assessment that is based on this, the selection of a robot with the corresponding safety functions, the selection of suitable additional safety components and, finally, validation.