Risks management and cobots. Identifying critical variables.

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ABSTRACT. A collaborative robot or a "Cobot" is the name of a robot that can share a workspace with operators in the absence of a protective fence or with only partial protection. They represent a new and expanding sector of industrial robotics. This investigation draws from the latest international rules and safety parameters related to work with collaborative robots. Its detailed research is motivated by the design of a collaborative industrial robot system, hazard elimination, risk reduction, and different collaborative operations, such as power and force limiting, collaborative operation design, and end-effector safety requirements, among others. The purpose of our study is to analyze the most important variables that must be controlled in accordance with the desired use of the Cobot, according to ISO / TS 15066, ISO / TR 20218-1and some other generic safety regulations on machines and industrial robots. A series of observations and appreciations on the use of the Cobot will also be presented.

Keywords: Cobot, ISO/TS 15066, ISO/TR 20218-1, Risk assessment, Collaborative-robots.

1. Introduction

Since 2010, the demand for industrial robots has accelerated considerably. Between 2012 and 2017, average sales of robots stood at 19% per year. In 2017, robot sales increased by 30% to 381,335 units. The main drivers of this exceptional growth in 2017 were the metallurgical industry (+55%) and the electrical/ electronics industry (+33%).((IFR). 2018)

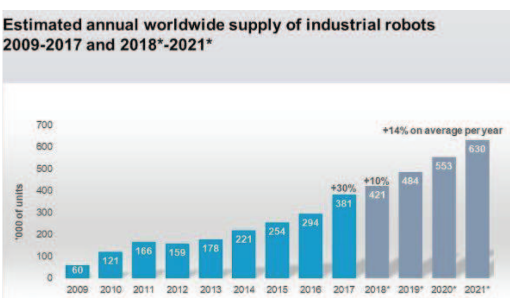

Fig. 1. Estimated annual worldwide supply of industrial robots. ((IFR). 2018)

The deployment of robotic applications has led to sustained advantages in product quality and economic efficiency. In many cases, unhealthy or hazardous tasks in the workplace are today assigned to robots rather than to human workers. In addition, further flexibility requirements continue to be imposed on manufacturing enterprises (Matthias et al. 2011). While in operation, conventional robots require physical barriers to protect their operators, because of high speeds and power demands during the production operations. Hence, a new kind of robot began to be used in industry, around 2010, with no protective fences or only partial guard rails. These new robots, called collaborative robots or "cobots"(Jocelyn, Burlet-Vienney, and Giraud 2017), combine the advantages of robots and their high accuracy, speed, and repeatability, with the flexibility and cognitive skills of human workers.(Villani et al. 2018) This new technology is designed not only for multinational enterprises, but also for medium and small companies, that change their operations frequently and, above all, require flexibility.
Converting the present day conventional robots to collaborative ones presents a lot of revenue potential. The conventional robots cannot be replaced with new collaborative robots because of the huge financial cost involved (Khalid et al.

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2016). According to the main manufacturer of cobots, over 31,000 of its collaborative robots have been sold for use in several thousand production environments on a daily basis throughout the world. Taking a baseline reference in 2018 of USD 710 million, the overall growth of the collaborative robot market is estimated to rise to USD 12,303 million by 2025, at a compounded annual growth rate (CAGR) of 50.31% throughout the forecast period. Significant global demand for cobots among Small and Medium Enterprises (SMEs) has also dynamized the market for these robots. (Markets and markets 2018).
Any new security regulations will have to focus on guaranteeing the security of the operator in the collaborative workspace; in addition, each country must adapt and improve upon its own regulations, to ensure the correct implementation of the cobots.

2. Analysis of Regulations

A general standard on the safety of machinery is given in EN ISO 12100. The primary purpose of this International Standard is to provide designers with an overall framework and guidance for decisions during the development of machinery to enable them to design machines that are safe for their intended use. It has the following structure:

- Type-A standards: basic safety standards for design and general aspects that can be applied to machinery
- Type-B standards: Can be applied to a wide range of machines. B1: Particular safety aspects. B2: Standards on safeguards.
- Type-C standards: Machine safety standards. Dealing with detailed safety requirements for a particular machine or group of machines. (ISO 12100 2010)

The main international standards on machine safety are as follows:

- ISO 10218-1. Robots and robotic devices. Safety requirements for industrial robots. Part 1: Robots.(ISO 10218-1 2011)
- ISO 10218-2. Robots and robotic devices. Safety requirements for industrial robots. Part 2: Robot systems and integration.(ISO 10218-2 2011)
- ISO 11161. Safety of machinery. Integrated manufacturing systems. Basic requirements.(ISO 11161 2007)
- ISO 13849-1 Safety of machinery. Safety related parts of control systems. Part 1. General principles for design.(ISO 13849-1 2015)
- ISO 13850. Safety of machinery. Emergency stop function. Principles for design.(ISO 13850 2015)
- ISO 13851. Safety of machinery. Two hand control devices. Functional aspects and design principles. (ISO 13851 2002)
- ISO 13855. Safety of machinery. Positioning of safeguards with respect to the approach speeds of parts of the human body.(ISO 13855 2010)
- IEC 61508-1 Functional safety of electrical/electronic/programmable electronic safety-related systems. Part 1. General requirements. (IEC 61508-1 2010)
- IEC 62061. Functional safety of safety-related electrical, electronic and programmable electronic control systems.(IEC 62061 2005)
- IEC 60204-1. Safety of machinery. Electrical equipment of machines. Part 1. General requirements.(IEC 60204-1 2016)

2.1 *ISO 10218-1 and ISO 10218-2*

This standard introduces a series of guidelines on how operations should proceed within the collaborative workspace. According to section 5.3.8.3, any failure detected in the safety features must result in a safety stop. It also describes four operating modes(ISO 10218-1 2011, ISO 10218-2 2011):

- Safety-rated monitored stop.
- Hand-guided
- Speed & Separation Monitoring
- Power and Force Limited

(The ISO/TS 15066 applies these 4 modes to the work in collaborative operations).

2.1.1 *Definitions*

Collaborative robot. Robot designed for direct interaction with humans in a defined collaborative space.
Collaborative operation and Collaborative workspace definitions are modified in ISO/TS 15066.

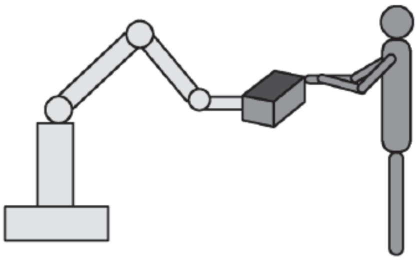

Fig. 2. Suggested labelling design for collaborative robots.(ISO 10218-2 2011)

2.2 *IEC 60204-1*

This international standard defines three categories of stop functions for the electrical equipment of machines:

Stop category 0: Stopping by immediate removal of power to the machine actuators. (Uncontrolled stop, for example.)

Stop category 1: A controlled stop with power available to the machine actuators to achieve the stop and the removal of the power when the stop is achieved.

Stop category 2: A controlled stop with power left available to the machine actuators. (IEC 60204-1 2016)

2.3 *ISO/TR 20218-2:2017*

This technical report supplements ISO 10218-2:2011 and provides additional information and guidance on reducing the risk of intrusion into hazardous zones in the design and safeguard of manual load/unload installations. (ISO/TR 20218-2 2017)

2.4 *ISO/TS 15066 (Technical Specification)*

A technical Specification for the Robots and robotic devices - Collaborative robots that provides guidance for collaborative robot operation where a robotic system and people share the same workspace. It is not a standard, although it is now accepted as best practice, together with ISO 10218 on human-robot collaboration. (Rosenstrauch and Kruger 2017)
The specification supports the industrial robot safety standards ISO 10218-1 and ISO 10218-2, and provides additional guidance on the identified operational functions for collaborative robots.(ISO/TS 15066 2016)

2.4.1 *Definitions*

Collaborative operation. State in which a purposely designed robot system and an operator work within a collaborative workspace. (ISO/TS 15066 2016)

Collaborative workspace. Space within the operating space where the robot system (with end-effector and workpiece) and human can perform tasks at the same time. (ISO/TS 15066 2016)

Quasi-static contact. Contact between an operator and part of the robot system, where the operator body part can be clamped between a moving part of a robot system and another fixed or moving part of the robot cell.(ISO/TS 15066 2016)

Transient contact. Contact between an operator and part of a robot system, where the operator body part is not clamped and can recoil or retract from the moving part of the robot system.(ISO/TS 15066 2016)

Protective separation distance. Shortest permissible distance between any moving hazardous part of the robot system and any human in the collaborative workspace. This value can be variable.(ISO/TS 15066 2016)

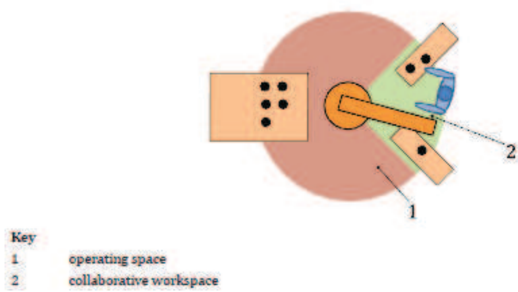

Fig. 3. Example of a collaborative workspace according to (ISO/TS 15066 2016).

This specification complements the four collaborative operating modes described in ISO 10218.

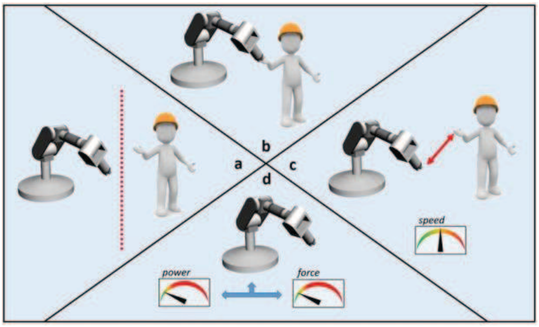

Fig. 4. ISO/TS 15066:2016 collaborative operative on modes.(Rosenstrauch and Kruger 2017)

2.4.2 Safety-rated monitored stop.

Allows robot motion only when the operator is outside the collaborative workspace. According to ISO 60204, this is a category 2 stop. In this stop, the drive power remains on and motion resumes after the operator leaves the workspace. Motion resumes without additional action. (Type a, Fig. 4.)
The main applications of this operating mode are:

- Direct part loading or unloading to end-effectors
- Work-in-process inspections.
- When operator or Cobot moves (1, not both) in collaborative workspace.

(Roberta Nelson Shea and Rockwell Automation)

As shown in figure 5, the Cobot system is only permitted to enter the collaborative workspace when an operator is not present in the collaborative workspace. If there is no operator in the collaborative workspace, the Cobot system may operate non-collaboratively. The collaborative workspace must be established with distances according to requirements of ISO 13855.

Robot motion or stop function		Operator's proximity to collaborative workspace: Outside	Operator's proximity to collaborative workspace: Inside
Robot's proximity to collaborative workspace	Outside	Continue	Continue
	Inside and moving	Continue	Protective stop
	Inside, at Safety - Rated Monitored Stop	Continue	Continue

Fig. 5. Truth table for safety-rated monitored stop operations.(Roberta Nelson Shea and Rockwell Automation)

2.4.3 Hand-guided.

The operator uses a hand-operated (Enable) device to transmit motion commands. Before the operator enters the collaborative workspace, the Cobot automatically comes to a safety-rated monitored stop. (Drive power remains on.) The operator holds a hand-operated device to activate motion/operation, as per ISO 10218-1 (5.6.4). These actuating guiding devices must be located at or near the Cobot end-effector.(ISO/TS 15066 2016) Non-collaborative operation resumes when the operator leaves the collaborative workspace. (Type b, figure 4). (Roberta Nelson Shea and Rockwell Automation)
The operator must have a full clear view of the collaborative workspace.(ISO 10218-2 2011)
Cobot systems used for hand guiding can have additional features, such as force amplification and virtual safety zones and tracking technologies.(ISO/TS 15066 2016)
If operator safety is dependent on limiting the range of motion of the Cobot, the Cobot will utilize safety-rated soft axis and space limiting according to ISO 10218-1 (5.12.3)(ISO/TS 15066 2016)
The main applications of this operating mode are:

- Cobot lift assistance.
- Multitude of tasks such as "manual tool".
- Small-batch production.

The operating sequence for hand guiding is also defined in this rule.

Nowadays, some cobots permit operators to “teach” them, thanks to a Hand Guidance function. It is used to teach the robot points or paths with less or even with no programming.(Fanuc 2019)
This must be also done with a hand-operated device according to ISO 10218-1.

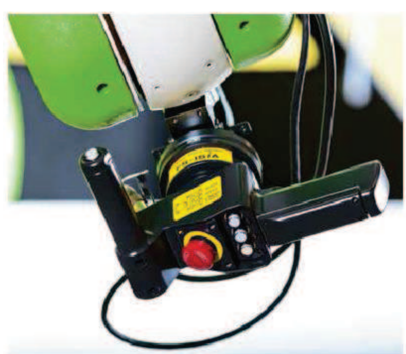

Fig. 6. Hand-operated device. (Guiding device).(Fanuc 2019)

The guiding device shall incorporate an emergency stop and an enabling device, unless the enabling device exclusion requirements found in 5.4.5 ISO/TS 15066 are met. The guiding device shall also be located in accordance with 5.5.3.2.2 of ISO/TS 15066. (ISO/TS 15066 2016)
Transitions between hand guiding and non-collaborative operations or other kinds of collaborative operations shall not introduce additional risk.(ISO 10218-1 2011)

2.4.4 Speed and separation monitoring.

Cobots must have protective devices that are used to guide any approach between an operator and a Cobot. An operator and the robot system may move concurrently in the collaborative workspace. Minimum protective separation distances between the operator and robot system is maintained at all times. As operator and robot approach each other, the speed is lowered (safety-rated) to maintain a minimum protective separation distance. If the minimum protective separation distance is violated, a protective safety-rated stop is required. Usually this minimum protective separation involves contact with the Cobot,(Roberta Nelson Shea and Rockwell Automation) which implies that there is a risk of impact that will to some extent be hazardous depending on the case. It is therefore advisable to observe this minimum protective distance. Power and force have to be limited according to harmless injury criteria.
The protective separation distance can be calculated based on the concepts used to create the minimum distance formula in ISO 13855, modified to take into account the following hazards associated with speed and separation monitoring. (Type c, figure 4). (ISO/TS 15066 2016)
The main applications of this operational mode are:(Roberta Nelson Shea and Rockwell Automation)

- Simultaneous tasks.
- Direct operator interface.

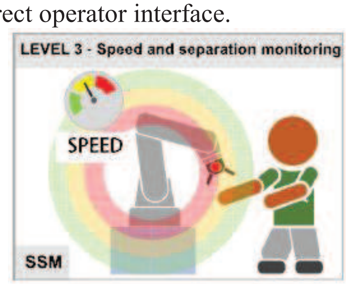

Figure 7. Speed and separation monitoring.(Villani et al. 2018)

2.4.5 Power and Force Limiting.

The operator faces multiple risks –tooling, end-effectors, sharp-edged workpieces, moving elbows - while using a Cobot. The speed is slower as the operator and the robot approach each other, even though unexpected collision or contact can always occur. (Type d, Figure 4)
Power and force are limited in the interests of safety and to ensure compliance with given biomechanical force or pressure thresholds defined in ISO/TS 15066.(Rosenstrauch and Kruger 2017)
The injury severity criteria according to TS 15066 working group were developed by the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA-BGIA). Project FP 317. The Pressure Pain Threshold (PPT) is defined as the minimum intensity of pressure that is perceived as painful. 100 healthy subjects (40 metal workers, 57 males, age range between 18 and 66 years) were assessed at 29 body sites in three measurement rounds. Inter-individual variability of PPTs was high.(BG/BGIA 2011)
The study established limit values for this body region.

Main body regions	Body region (BR) code	Individual body regions
Main region 1 : Head with neck	1.1	Skull/Forehead
	1.2	Face
	1.3	Neck (sides/neck)
	1.4	Neck (front/larynx)
Main region 2 : Trunk	2.1	Back/Shoulders
	2.2	Chest
	2.3	Belly
	2.4	Pelvis
	2.5	Buttocks
Main region 3 : Upper extremities	3.1	Upper arm/Elbow joint
	3.2	Lower arm/Hand joint
	3.3	Hand/Finger
Main region 4 : Lower extremities	4.1	Thigh/Knee
	4.2	Lower leg
	4.3	Feet/Toes/Joint

Figure 8. Body model with main regions.(BG/BGIA 2011)

ISO/TS 15066 defines maximum pressure and force values for specific body areas and declares contact with face, skull and forehead not permissible.

2.4.5.1 *Graphical representation of acceptable and unacceptable forces or pressures*

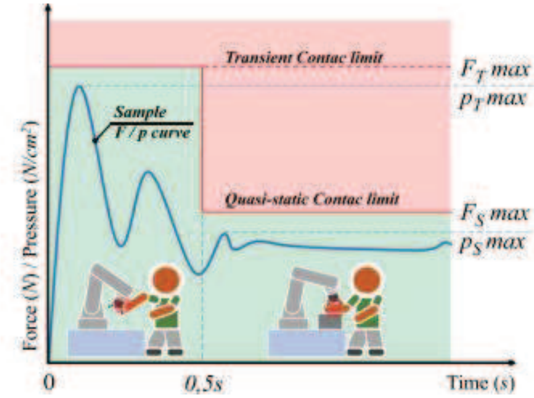

Fig. 9. Representation of acceptable (green) and unacceptable (red) forces or pressures. (Villani et al. 2018)

The maximum permissible force is based on the lowest energy transfer criteria that could result in a minor injury, such as bruising, equivalent to a severity of 1 on the Abbreviated Injury Scale (AIS). The values shown in ISO / TS 15066 will change in the future for the values of a more specific investigation with collaborative robots.(ISO/TS 15066 2016)

BGIA Studies also gives limit values of the injury severity criteria for maximum pressure/Surface pressing and compression constant.(Joe Falco, Jeremy Marvel, and Rick Norcross 2012, BG/BGIA 2011)

2.5 *ISO/TR 20218-1:2018 (Technical Report)*

This technical report provides guidance on safety measures for the design and integration of end-effectors used in robot systems. From the manufacturing, design and integration of end-effectors to the information necessary for their use.(ISO/TR 20218-1 2018)
This technical report also mentions shape and surface forms, safety-related control system performance, examples of hazards from end-effectors and workpieces, etc.

2.5.1 *Definitions*

End-effector. A device specifically designed for attachment to the mechanical interface that enables the robot to perform its task.(ISO/TR 20218-1 2018)

If the end-effector is intended for use in a power and force limited collaborative operation, a means to establish the threshold limit values is provided in ISO/TS 15066:2016 Annex A. (Tables 2 and 3).(ISO/TR 20218-1 2018) Risk reduction measures are taken to minimize risks posed by sharp edges and to prevent motion where edges can result in unacceptable contact force or pressure. Protective measures, such as reduced sharp edges, minimized end-effector mass, increased surface area, using different surface materials… can all be implemented. End-effectors can also be designed to provide protection from workpiece-related hazards.(ISO/TR 20218-1 2018)
ISO/TR 20218-1 recommends using protective devices and safety control systems such as:

- Force sensing
- End-effector path planning
- Grip force
- Speed monitoring (according to ISO/TS 15066)
- Presence sensing. (These devices comply to the applicable parts of IEC 61496; integration of these devices is in accordance with ISO 10218-2:2011, 5.2)
- Compliant link
- Functional safety requirements. (According to ISO 10218-2)
- Emergency stop. (According to ISO 10218-2 and IEC 60204-1 stop categories)

(ISO/TR 20218-1 2018)

Recommendations are given on gripper end-effectors such as grasp-type grippers, vacuum grippers and magnet grippers.
In hand-guiding robots, operations that involve moving loads in a gripper could provide the means to open and close the gripper.
Instructions for the safe use of end effectors are provided, such as clamp release conditions, and the risk of falling workpieces due to a loss of power.
The annexes also provide practical examples for end-effector risk assessment, safety performance gripper designs, and examples of hazards, their origins and potential consequences.(ISO/TR 20218-1 2018)

Fig. 10. End-effector.(OnRobot 2019)

3. Conclusions

Despite the fact that some regulations, technical specifications, technical reports and researchers are trying to address the potential dangers of this type of robotics there are still many critical and dangerous aspects to consider. Security is closely associated with safety as both of these characteristics have to be addressed synchronously (Khalid et al. 2018).

ISO/TS 15066 defines pain threshold limits, but, what happens if that limit value of force is reached in a contact between an operator and a workpiece, and the workpiece is, for example, a steel plate with sharp edges? This technical specification also states that contact between Cobot and Operator face, skull and forehead areas are not permissible,(ISO/TS 15066 2016) which implies that the operator must wear some type of approved protective head gear whenever exposed to a risk of contact, otherwise, some other sorts of preventive measures should be implemented.

Other studies also showed the need to carry out more detailed safety studies on this type of robot. "The TS 15066 working group must develop more detailed test device requirements for robots with power and force limiting functionality".(Joe Falco, Jeremy Marvel, and Rick Norcross 2012) "The most important statement of ISO/TS 15066 is an implicit one: a safe robot does not exist, at best safe applications. But safety here means that there is still a risk of serious injury". (Rosenstrauch and Kruger 2017)

The market for collaborative robots is growing at a very fast rate and the risks derived from the use of this type of technology must be thoroughly tested, as not only industrial, but also domestic cobots will be very present in the our surrounding environment.

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