WhitePaper

Safety in Human-Robot-Collaboration

Risk Analysis and Minimization

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Human-Robot-Collaboration

Risk Analysis and Minimization

Second edition

Vienna, 15.05.2017

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Human-Robot-Collaboration

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Abstract

The topic of **Human-Robot-Collaboration** (**HRC**) is becoming increasingly manifested as a key element of the Industry 4.0 vision of the future, not just in science but more and more in industry too: New robots that are suitable for direct collaboration with humans are appearing on the market at ever shorter intervals and human-robot-collaborations have been implemented successfully in more and more processes.

The first joint publication by **TÜV AUSTRIA** and **Fraunhofer Austria** outlines the basic normative requirements on the collaboration between humans and robots that have to be taken into account in the development of an integrated safety & security concept for human-robot-collaboration. In this **second edition of the white paper series, the practical side of functional safety in human-robot-collaboration** will be examined in more detail.

Following the implementation of an HRC demonstrator in the pilot factory Industry 4.0 of TU Vienna and the development of an HRC application together with the company Magna Steyr Fahrzeugtechnik, this present edition provides an insight into the steps necessary to implement a human-robot-collaboration with respect to guaranteeing the functional safety. Furthermore, an overview of the most important technical tools for the assessment of such applications will be presented. It becomes clear that apart from technical mechanisms and complex measurement methods, simple constructive and organizational measures can also contribute to reducing the risks in the collaboration between humans and robots. A decisive contribution is made here by the **Institute of ROBOTICS of the JOANNEUM RESEARCH** within the scope of an associated project partnership.

The overriding framework to achieve this risk reduction is the **risk analysis**, which follows clear specifications that are standardized in EN ISO 12100. In the present white paper, the performance of the risk analysis is explained point by point for the HRC application in its sequence. This should provide a basic understanding of the logics and the contents of the structured risk analysis and hence counteract one of the main obstacles to realizing human-robot-collaboration from the point of view of industry, namely the uncertainty of its implementation. At the same time, however, this should not belie the sound practical knowledge that is needed during the identification, quantification and reduction of risks, as possessed by institutions and companies who support the performance of risk analyses day in, day out on behalf of industry.

In order to further illustrate the growing practical relevance of the topic, the paper begins with **two exemplary applications of human-robot-collaboration** – one from Austria's academic and the other from its industrial sector. An exemplary procedure for an **initial profitability assessment of HRC applications** during introductory projects rounds off this edition in the series of publications.

1. HRC applications

1.1 *Use Case 1: Final assembly – TU Vienna pilot factory Industry 4.0*

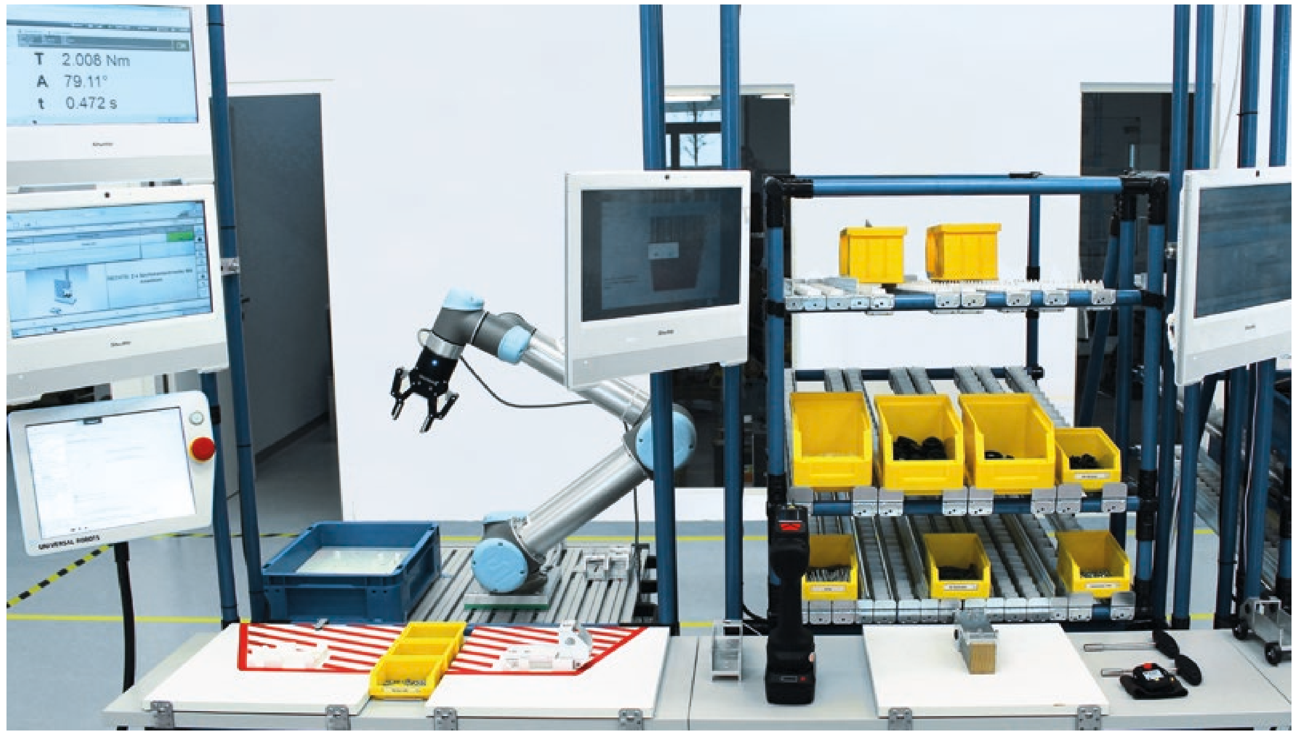


Fig. 1: Set-up of Use Case 1: Final assembly – TU Vienna pilot factory Industry 4.0

Key info	*Robot:* Universal Robot UR5 CB3	*Maturity:* Demonstrator
	Type of collaboration: Cooperation	*Process area:* Assembly

Application

The sensitive robot removes bodywork parts for a model truck from a delivered small load carrier and places these in the assembly devices at the workplace. The employee joins the positioned parts together by a screw connection. By using two assembly devices at the workplace, the human and the robot can work in parallel and simultaneously at the workplace and rotate alternately between the two devices.
The robot is also responsible for transferring the workpiece from the first to the second assembly device.

A model truck was chosen as a product because it reflects the complexity of an industrial task. Future plans envisage the integration of the HRC cell in the manufacture of a 3D printer.

Goals

- Improved ergonomics (force-controlled pick-up of the workpiece from the first assembly device)
- Increased productivity of the working system through the parallel use of humans and robots

Product data	*Product*	*Dimensions*	*Components*	*Weight*
	Model truck (3 variants)	ca. 250x100x100 mm	ca. 20 units	ca. 250 g

Safety concept

Robot

- Reduction of force and output
- Adjustment of speed

Surroundings

- Marked by warning signs and light signal columns
- Maintenance of a minimum distance between the robot and workplace set-up
- Avoid sharp edges and corners

Tool

- Covers for gripper kinematics and enlarge area of the gripper tips
- Secure the tool interface at the flange by a protective ring
- Guide the tool's leads through a tunnel system

Program

- Vertical design of paths avoids shear points
- Monitor the gripping force to detect incorrect objects (not safety-based)

Certification

- Self-certification
- Risk analysis supported and moderated by TÜV AUSTRIA

1.2 *Use Case 2: Final vehicle assembly – Magna Steyr Fahrzeugtechnik*

Key info	*Robot:* KUKA LBR iiwa 14 R820	*Maturity:* Demonstrator
	Type of collaboration: Cooperation	*Process area:* Final vehicle assembly

Application

Two completely independent application examples taken from a series process are symbolic for the flexible use of a mobile, lightweight robot. A simple change of gripper, the quick, needs-based movement from one to the other application and rough positioning at the new workplace are sufficient to indicate to the system which task it then has to perform. After a minimum set-up time, the mobile overall system supports employees at the existing workplaces, thus strengthening agile production concepts.

Use Case 2.1. shows the removal of door panels from a shelf and the subsequent test process for the door panel, which takes place primarily with the help of a camera. The mobile manipulator hereby performs a job that is ergonomically unfavorable for humans, and the non-value-creating share of the visual quality testing process.

In Use Case 2.2., the lightweight robot removes a number of limp objects from a shelf with the aid of a modular gripper/camera solution that has been developed within the scope of the application case. The pick-to-light system installed for humans in the shelf informs the robot system by means of signal lamps of which objects are released for removal, thus allowing a smooth "collaboration." Both use cases end when the components are set down on a workbench that it used by the robot and humans or when they are handed over directly to the employee.

Goals

- Realization of agile production concepts
- Reduction of non-value-creating process contents
- Avoidance of ergonomically unfavorable, manual work

Product data

Product	*Dimensions*	*Weight*
Vehicle panels	ca. 685x550x5 mm	ca. 4500 g
Limp objects	ca. 200x150x3 mm	ca. 10–300 g

Safety concept

Robot

- Reduction of force and output
- Adjustment of speed

Surroundings

- Marking of the cooperation area

Tool

- Enlargement of the collision areas through a suitable design
- Avoidance of moving parts through positive-locking gripping of the panels
- Constructive force-limited mechanism when gripping the limp objects

Program

- Flexibility control

Certification

- Self-certification

Fig. 2: Set-up of Use Case 2: Final vehicle assembly – Magna Steyr Fahrzeugtechnik

2. Risk analysis

Structured method to achieve the safety goals (CE-conformity)

Both of the use cases shown here are a combination of various technical components – robot arm, control system, robot tool, as well as the surrounding elements such as workbench or storage and materials handling technology. Only this combination and collaboration with humans results in an HRC application pursuant to EN ISO 10218-2 and a machine from the point of view of the Machinery Directive 2006/42/EC, that may only be placed on the market and thus put into operation, if it is in line with this regulation, amongst others, and thus its CE-conformity has been tested and confirmed.

The safe functions also have to be proven by the owner based on national regulations, in Austria the Federal Act on Safety and Health Protection at Work (ASchG and AM-VO).
These requirements have already been explained in more detail in the first white paper in this series (see **www.tuv.at/i40**).

A central and compulsory element of the risk conformity assessment is a risk analysis. The procedure is described in EN ISO 12100 and has to be performed by the distributor.

The four core steps of the procedure will be described in the following, taking the HRC application in the pilot factory Industry 4.0 of TU Vienna (Use Case 1) as an example. The documentation of the risk analysis in practice is supported in a suitable digital form, for example versioned text and table files.

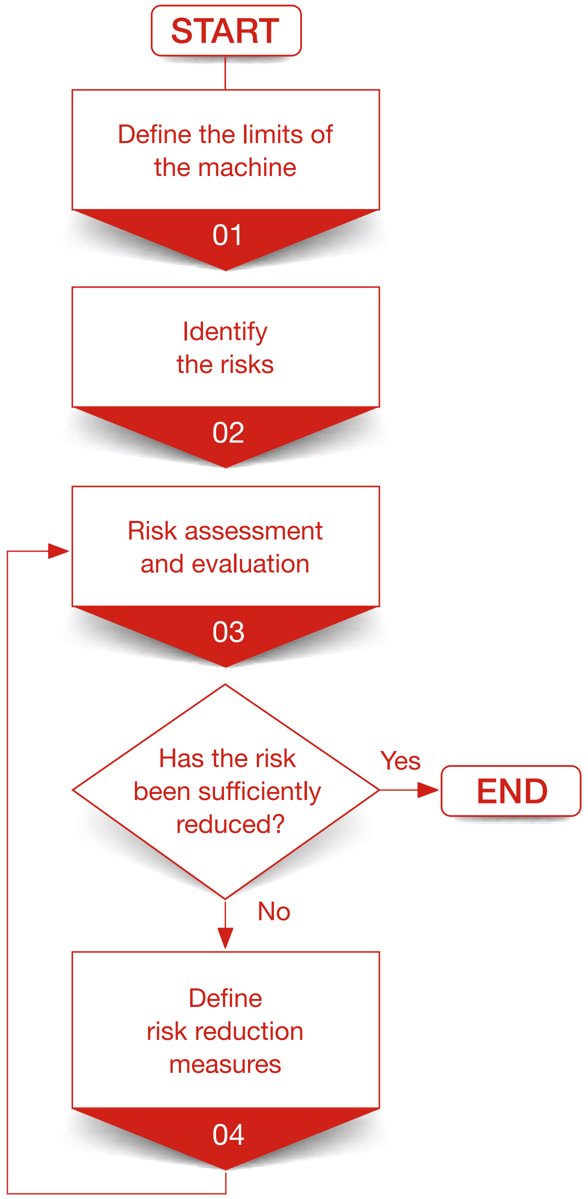


Fig. 3: Risk analysis procedure

2.1 Defining the limits of the machine

By specifying the machine limits the scope of the examination for the risk analysis is defined. In this case it is an assembly system to assemble products in which the robot and humans share the work. It also describes the features and performance of the machine as well as spatial, temporal and a number of other limits such as the conditions of use and personnel qualifications.

Spatial limits refer to spaces in which the machine can move and the space requirement for the operator as well as interfaces to upstream and downstream machines and stations. Temporal limits describe the service life and maintenance intervals for the machine, for example. Thus, the service life of the robot model UR5 that is used in the first Use Case is 35,000 hours according to its manufacturer, something that also has to be taken into account in the service life of the overall HRC application.

2.2 Identifying the risks

Risks that arise from the use of the machine for its operator can be identified as soon as transparency has been achieved on the scope of the examination. Workshop formats have proven their worth for this analysis, where various internal and external experts, which are or are not familiar with the application, identify possible risks along the service life phases (see Fig. 4) of the HRC application through a methodical discussion of concept, drawings, process illustrations and technical data for the application under assessment.

Endangered persons in this case are not just the actual machine operators but also technicians, cleaning personnel or external visitors to the production environment. The **moderation** of this kind of workshop is best placed in the hands of **independent institutions with sufficient knowledge of the assessment methods** to avoid any conflict of interests.

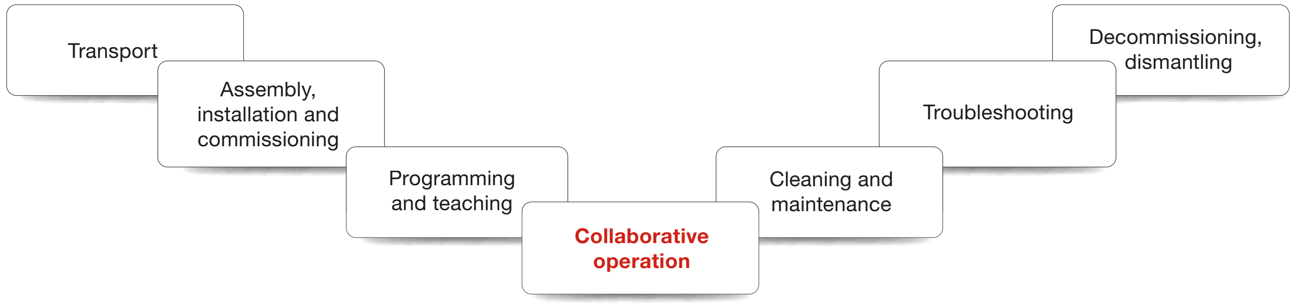


Fig. 4: Service life phases of an HRC application

It helps to identify possible sources of risks in a structured way for this analysis in addition to the obligatory consideration of all service life phases. Apart from direct mechanical risks, arising above all from the robot as an actuated system and other manipulation stations, electrical and ergonomic risks are other significant risk dimensions that are relevant for the HRC.

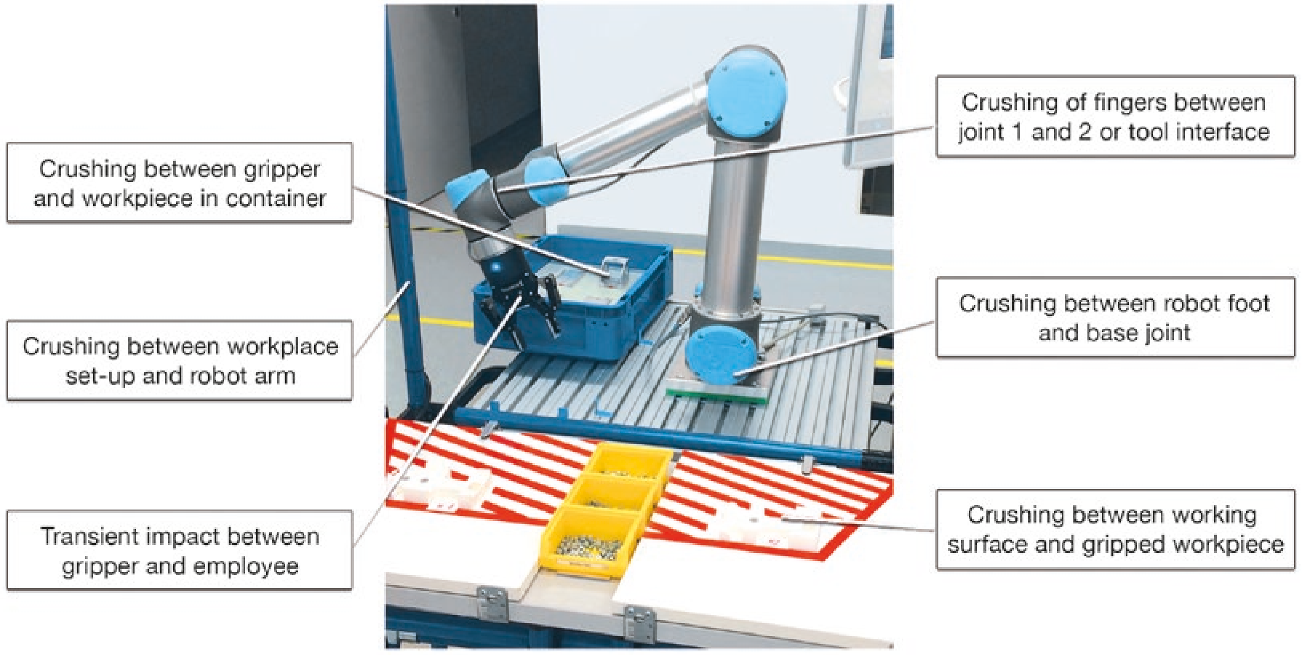


Fig. 5: Identified collision risks

Ergonomic risks relate to a potentially high work monotony, for example, resulting from the fact that the robot takes care of a large share of work, leaving only minor tasks for the machine operator, or from an unfavorable arrangement of operating and control displays. Other key risks in a work system, such as hazards from substances and noise, are not dealt with in this document because they are not directly related to HRC.

One main risk that also illustrates the degree of novelty of HRC applications compared to classic robot applications is the potential possibility of a collision between humans and the robot in the direct collaboration, without any further safety devices. Possible collision points have to be identified here within the scope of the risk analysis. Figure 5 shows exemplary collision points that were identified during the risk analysis of the HRC Use Case in the pilot factory Industry 4.0 of TU Vienna.

2.3 Risk assessment and evaluation

Once all of the risks have been identified, they have to be assessed. Whereas the identification phase is based on a subjective judgement of the assessing persons, defined parameters are used to quantify the risks, which at the same time means an objectification of the process. Each identified risk can be evaluated according to four criteria:

S: Extent of damage at the start of the risk
F: The frequency and duration for which a human is exposed to the risk
W: The probability of a risk occurring
P: The avoidability of damage by recognizing the occurrence of the risk

Each risk is assessed according to each of these criteria. Various standards provide different methods and scales for this purpose, whereby these do not have to be mutually compatible. Nor do uniform rules apply for their representation in so-called risk graphs. The following definition has proven its worth:

- The **extent of damage** S has a bandwidth from 0 (no damage) to 4 (irreversible damage, loss of parts of the body, death).
- The **frequency** F lies between 1 (exposure to risk less than once a year for fewer than 10 minutes) and 5 (exposure to risk more often than once per hour). The highest frequency level 5 thus has to be assumed for a number of risks during continuous operation of an HRC application.
- For the **probability of occurrence** W, values are assumed between 1 (negligible) to 5 (very high).
- The **avoidability** P of the damage is defined between 1 (recognition of the risk occurrence and avoidance is likely) and 5 (recognition and avoidance is impossible).

So-called aggregated values are then calculated from these individual assessments, namely the risk class and the risk priority number.

Risk class = F + W + P

Risk priority number (RPN) = Risk class x S

The example in Figure 6 from Use Case 1 shows an identified collision risk as well as its quantification according to the aforementioned schemes, leading to an RPN of 30.

However, the figure that is calculated is only meaningful in comparison with a predefined, accepted residual risk. The accepted residual risk is defined in terms of quality by the team that prepares the risk assessment and takes statutory regulations into account (=safety goals of the machinery directive), and is regarded as a maximum RPN that may not be exceeded.

The goal is to reduce the identified risk with its RPN as far as possible in accordance with the ALARP (as low as reasonably possible) principle, though at least to a level below the defined accepted residual risk. Accordingly, risk-reducing measures have to be taken until the agreed RPN level is reached.

	Machine									Creation date	Accepted residual risk					
	Mechanical risks	Risk before									Risk after					
Ser. No.	**Risk** Description of risk / danger spot on the machine	S(0, 1-4)	F(1-5)	W(1-5)	P(1, 3, 5)	Risk class	RPZ	PLr	SIL	**Measure(s)** Description of measures taken, or still to be taken, including substantiation of measures (e.g. change of PL compared to risk graphs)	S(0, 1-4)	F(1-5)	W(1-5)	P(1, 3, 5)	Risk class	RPZ
	Mechanical risks															
102	A moving part approaches a stationary part resulting in crushing of a part of the body, in particular hands and arms	3	5	2	3	10	30	c	1	**Measure 1:** technical, limitation of the robot's force (F), possibly also robot performance (W) and speed of movement (v) to a level that reduces the risk of injury from crushing to an acceptable level	1	5	2	3	10	10
		1	5	2	3	10	10			**Measure 2:** organisational, increase the distances between moving and stationary parts taking the minimum distances into account	1	5	2	2	9	9
		1	5	2	2	9	9			**Measure 3:** organisational, attach a light signal to indicate an operative robot	1	5	2	1	8	8

Fig. 6: Risk identification, assessment and reduction with the help of risk priority numbers

2.4 Risk reduction

By implication, all identified risks that are rated with an RPN above the agreed level have to be reduced by appropriate measures. A differentiation is hereby made between constructive, technical and organizational measures. Constructive measures relate to structural modifications to the machine that change its basic design or function. Technical measures are achieved with aids of a technical nature. These can be additional safety devices or sensors with respect to a human-robot-collaboration, though also the limitation of output and speed by means of the robot's control system.

Depending on the RPN, a certain degree of reliability that describes the failure probability per hour of the technical measure is assumed for control technology measures. This presumed degree of reliability is quoted as the Performance Level (PL) according to EN ISO 13849-1 or Safety Integrity Level (SIL) according to EN 61508 and EN 62061.

In Figure 6, the exemplary risk with its RPN of 30 requires the use of a technical measure to reduce the risk to a Performance Level of at least PL = c and/or a Safety Integrity Level of SIL1, corresponding to a maximum failure probability of 0.0003% per hour. The RPN is reduced to 10 if these measures are implemented.

It can be reduced even further by supplementary organizational measures, in the present example to 8. If this is then below the agreed maximum value, no further measures would be necessary. There are a large number of different ways to reduce the risks and their effects are very different too.

The specific feature of a human-robot-collaboration lies in the potential collision between a human and the robot. The following chapters offer an overview of how to deal with this specific feature as well as further ideas for risk-reducing measures.

Performance Level (PL)	Probability of a hazardous failure (PFH$_d$) [1/h]	SIL Level
a	$10^{-5} \leq PFH_d < 10^{-4}$	-
b	$3 \times 10^{-6} \leq PFH_d < 10^{-5}$	SIL 1
c	$10^{-6} \leq PFH_d < 3 \times 10^{-6}$	SIL 1
d	$10^{-7} \leq PFH_d < 10^{-6}$	SIL 2
e	$10^{-8} \leq PFH_d < 10^{-7}$	SIL 3

Fig. 7: Degrees of reliability of technical risk reduction measures

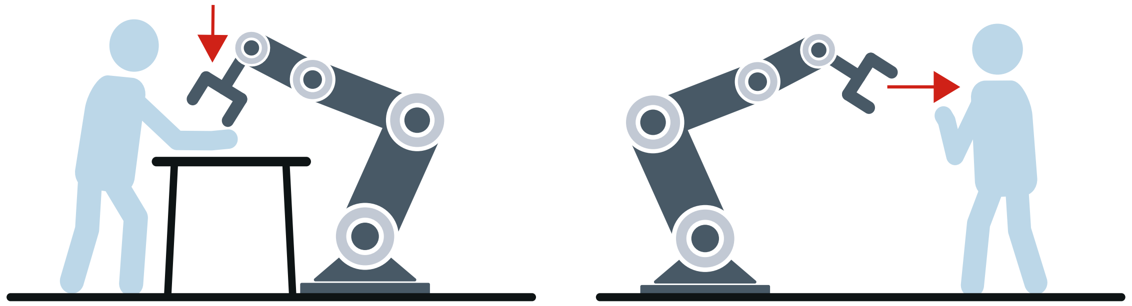
3. Risk reduction measures

3.1 Fundamentals of biomechanical limits

Once the possible collision scenarios between humans and robots have been identified in a risk analysis, the most important risk-reducing measure, after an avoidance of the danger spot, is to reduce the forces and speeds as a technical measure – so as to comply with the force and pressure limits that apply for collisions between the operator and robot.

The potential contact situations can be classified into two categories pursuant to ISO/TS 15066: **transient** and **quasi-static contact**. These differ firstly in terms of the duration of the contact and secondly as to whether it is possible for the person affected to free himself after the collision.

Quasi-static contact lasts for longer than 0.5 seconds per definition and the human is trapped between the robot and the surroundings or parts of the robot. In contrast, transient contact lasts a maximum of 0.5 seconds and the affected person can withdraw or step out of the way after contact (see Fig. 8 – transient and quasi-static).



Quasi-static collision

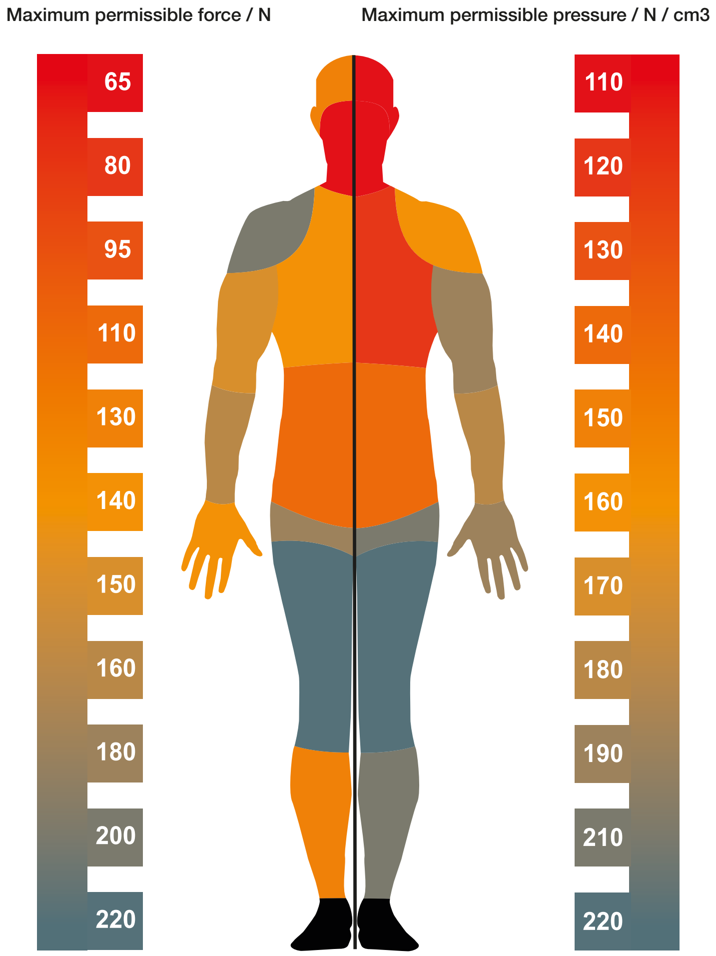
Transient collision

Fig. 8: Classification of collision situations

In order to define the limits for a quasi-static collision, the pain thresholds of humans were determined empirically for 29 specific regions of the body as a function of the effective force and pressure The Institute for Occupational Safety and Health (IFA) and the University of Mainz carried out a study with 100 test persons in 2014.
Although the results obtained will not be representative equally for everyone on account of the low number of random samples (e.g. differentiation between men - women), the limits that were identified were published in an information of the German Social Accident Insurance (DGUV) (3) and the technical specification ISO/TS 15066:2016(E) (1). An exemplary excerpt is cited graphically in Figure 9.

ISO/TS 15066:2016, which supplements the standard EN ISO 10218-1/2:2012, also quotes limits for transient contact in addition to the described limits for quasi-static contact (see Fig. 9). For transient contact a limit twice as high as that for quasi-static contact is assumed, whereby this is a constructive estimate.

During a possible collision between humans and robots, both of the limits, force and pressure, which apply for the affected regions of the body, may not be exceeded according to ISO/TS 15066:2016. For small collision areas the pressure will be more relevant, whereas the effective forces will be more relevant for larger areas.



The exemplary biomechanical limits shown are a good orientation aid when implementing HRC applications in industry and can be used as a guideline.

Even if force, output and speed limits can be parameterized in the control systems of modern, collaborative robots, real measurements of effective forces and pressures in the context of the overall application should still be carried out – in fact for all collision cases identified during the risk analysis (see Fig. 5).

So compliance with the limit values is checked.

Fig. 9: Biomechanical limits pursuant to ISO/TS 15066:2016 for quasi-static contact (excerpt)

3.2 Measurement methods and aids

Different methods and equipment are available to perform these measurements, each of which is suitable for different measurements and purposes.

Force-pressure measuring device

The most informative measurement results are provided by combined force-pressure measuring devices such as the KDMG-KOLROBOT that has been developed by the Institute for Occupational Safety and Health (IFA) of DGUV. This measuring device realistically simulates the different regions of the body, each with their respective spring stiffness, as a biofidelic substitute and is even able to measure pressure in their local resolution.
Force and pressure curves can be determined in a single collision test. A piezo load cell is installed in the measuring device's housing to determine the force and a sensor film is attached to the collision surface, as can be seen in Figure 10, to measure the spatial distribution of this force, thus allowing the calculation of the pressure distribution. The data from the different sensors is compiled in an analytical software program.

Figure 11 shows how the maximum force exerted by the robot during a collision can actually be reduced by gradually lowering the force limit (S) and acceleration (a) in the control system of the tested robot, thus allowing the HRC application to be aligned to the biomechanical limits.

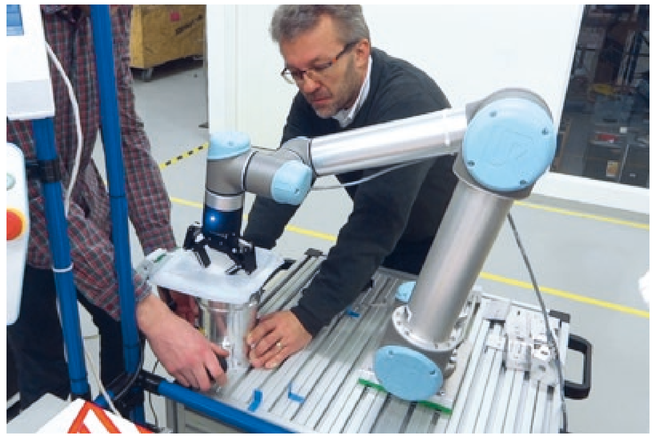


Fig. 10: KDMG-KOLROBOT measuring device in use

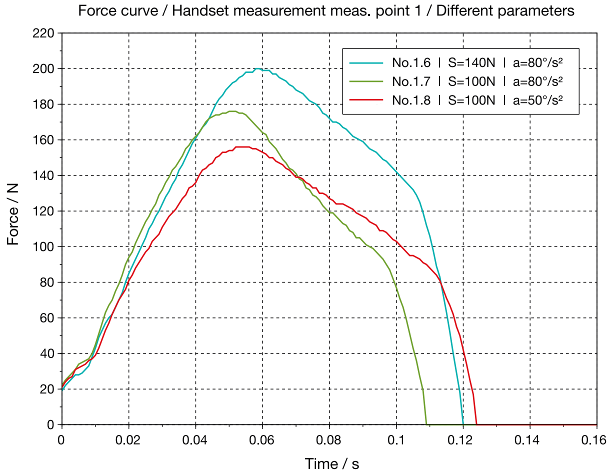


Fig. 11: Force/time curves with altered force and acceleration settings on the robot

By showing the force and pressure over a time curve, the duration of the load can be determined and thus a decision taken on which points in time the limit for quasi-static or transient contact situations has to be taken into account. The active and passive functions of certain robots mean that the forces and pressures are only active for a short time.

If one considers Figure 11 in more detail it can be seen that despite a parameterization of the force limit/sensitivity to 140 and 100 N in the robot's control system, higher peak forces were in fact reached in all three collision tests.

It can therefore be assumed that the robot only detects the occurred collision when the preset threshold is reached and it continues to build up force in the so-called run-on until the stop is triggered.

This phenomenon could also be proven by JOANNEUM RESEARCH (see Fig. 12) in further series of tests.

This proves that the parameters in the robot's safety settings are only proxy values that have to be checked by means of biofidelic measurements (4).

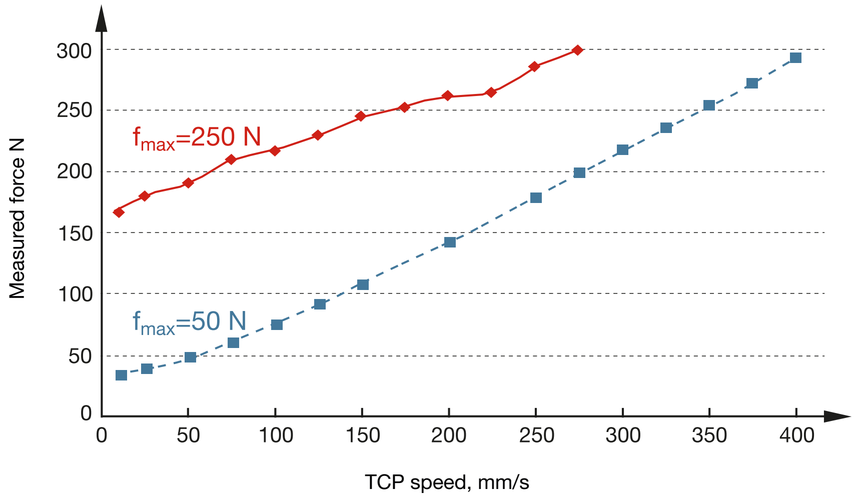


Fig. 12: Set sensitivity and actual collision force (4), robot model Universal Robot UR3

Hand-held instruments

In addition to the relatively large and cumbersome force-pressure measuring devices, hand-held instruments allow you to carry out force measurements in places that are difficult to access – for example between the jaws of a two-finger gripper – to determine the actual gripping force.

Fig. 13: Hand-held KMG-300 in use

Fig. 14: Results shown on a hand-held instrument (2)

The hand-held instruments can only measure the force over time. with a preset spring stiffness of 75 N/mm and a very limited range of additional attenuators, only very few constants of the regions of the body can be mapped.

Additional attenuators have to be attached to the outside of the device for this purpose. Alternatively, the pressure distribution can be determined by attaching pressure sensing films to the collision surface.

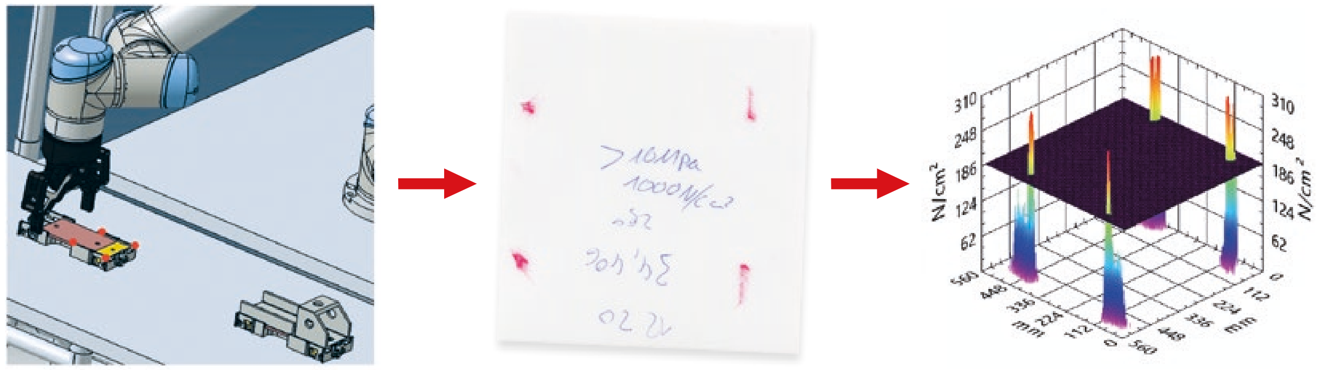


Fig. 15: Protruding crushing points on the assembly device, pressure sensing film with ink markings after the collision test and evaluation on the computer (biomechanical limit shown as a horizontal plane).

Pressure sensing films

Pressure sensing films are also suitable additional measuring devices to determine pressures at irregular geometries or at collision points that are even more difficult to access.

The films are coated with ink droplets and change color under a mechanical load. After a collision test has been performed, the pressure sensing films are scanned and evaluated with the help of software. As a result, pressure extremes can be localized precisely and structural changes to the HRC application derived as necessary.

3.3 Programming for Human-Robot-Collaboration

Technicians have to rethink the entire programming process in human-robot-collaboration through the parameterization of limits for force, output and speed so as to comply with the biomechanical limits in the robot control system.

Instead of minimizing cycle times through the shortest possible travels and high speeds for the robot, the program design itself should contribute to avoiding any risks without having too much of a negative effect on the performance.

The following points are just some possible measures:

- Gripping points as potential crushing points should be approached more slowly than in conventional robot programs.
- Gripper spreads should be designed as narrow as possible at the place of gripping itself to prevent fingers getting caught between the workpiece and gripper.
- During gripping, the buildup of force in relation to the gripper spread can be monitored to check if the correct object has been gripped.
- The trajectories should be planned at an adequate distance from surrounding objects to avoid additional collision risks.
- The speed curve within a path should be adapted to the direction of movement as well as the position of obstacles and persons.
- The robot should approach level surfaces at a right angle wherever possible so as to avoid shearing collisions.
- Preference should be given to positive over non-positive gripping processes where this is allowed by the object geometry.

Programming HRC applications calls for novel approaches compared to conventional industrial robots and poses new challenges for programmers. Personnel training is urgently needed here and the topic has to be dealt with accordingly during vocational training.

3.4 Constructive and organizational safety measures

Apart from the technical measures, above all the limitation of collision forces, constructive and technical measures to reduce risks also play an important role in the integral safe design of HRC applications. The structured approach of a risk analysis also identifies risks that can be combated by constructive or organizational measures. These risk-reducing measures are often cheaper and easier to realize.

With respect to the robot

Simple constructive elements can obstruct or even completely prevent access to potential shearing and crushing points so that these do not have to be monitored by complex technical means (see Figs. 16 and 17). This is necessary in any case if technical monitoring is impossible or the forces and pressures acting at potential collision points cannot be reliably determined by measurements, for example on account of their restricted spatial accessibility.

Enlarging the area of small contact surfaces such as gripper tips can distribute the collision forces over a larger area and hence reduce the pressure. Soft attenuators on the robot housing reduce the transmission of peak forces.

Laying media lines in a duct along the robot housing can greatly reduce the risks of damage to the system or injuries due to the cable becoming entangled (see Fig. 18).
At best, an external cable bundle should be avoided wherever possible and sole preference be given to the use of media lines that run inside the robot arm.

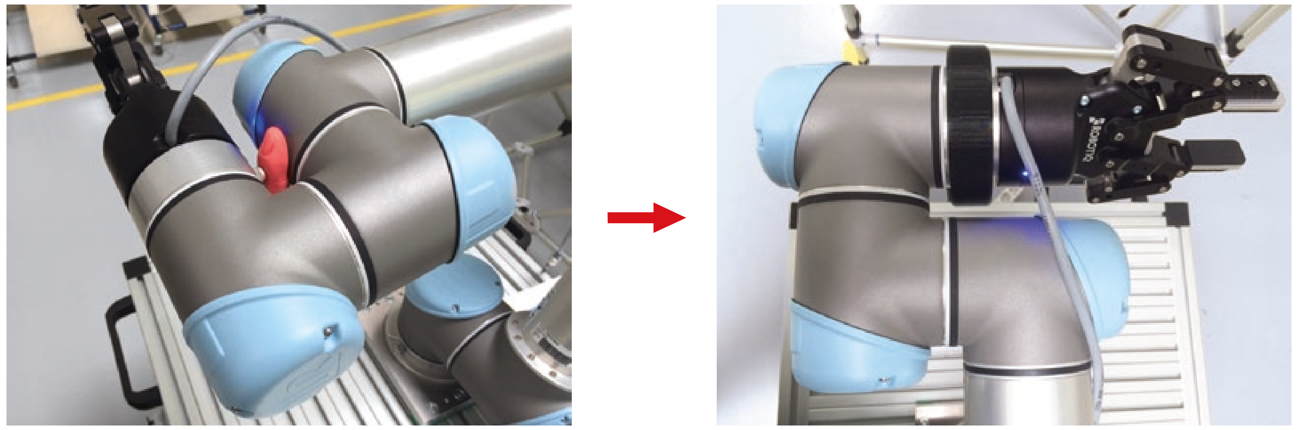


Fig. 16: left: Checking a crushing point on a workpiece flange with a safety finger, right: Protection with a protective ring

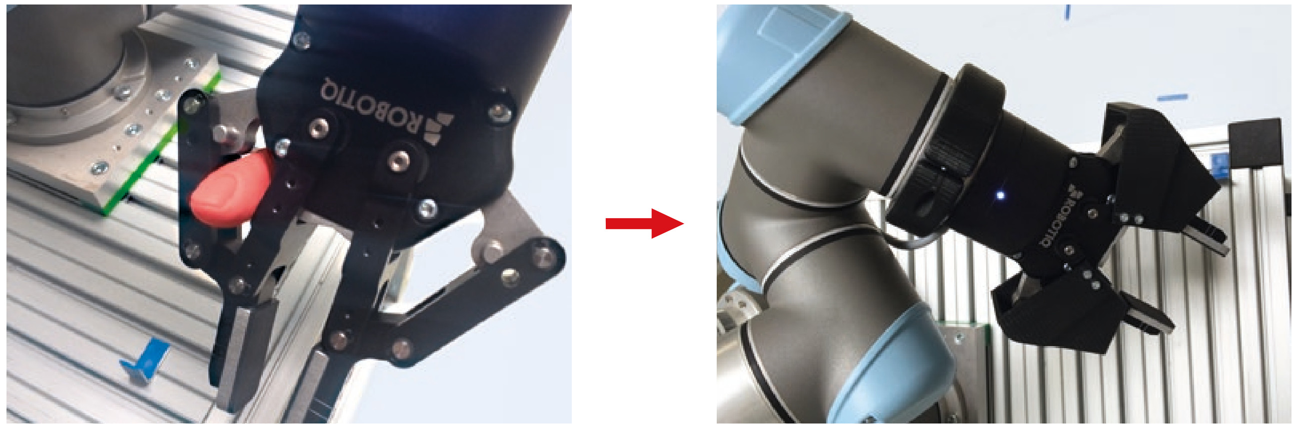


Fig. 17: left: Checking a crushing point on the exposed gripper kinematics with a safety finger, right: Protection with covers

Fig. 18: Installation of a raceway (6)

With respect to the operational area

Identifying the operational area of collaborative robots by warning signs (see Fig. 19) and the optical marking of the robot's range of motion within the collaborative workspace are expedient measures. These help attract attention to possible risks and increase the chances of recognizing the onset of a risk and thus of avoiding any damage or injury. In addition, the robot's operation is not interrupted by frequent safety shutdowns as a result of this. Status displays such as light signal columns indicate the operating state of the robot and prevent elements of surprise.

A sensible arrangement of the control panel in the collaborative working area also allows immediate access to the emergency stop equipment and an overview of fault and error messages. If there is increased visitor traffic in the affected production area, access to the operational area of the HRC application(s) should be restricted to authorized persons. In view of the direct collaboration area and its constructive design, preference should generally be given to large over small areas as well as rounded instead of square shapes. In the event of a collision, these measures mean that the largest possible force-absorbing area is provided, thus reducing the effective energy input.

Fig. 19: Warning sign HRC (3)

The example in Figure 15 clearly shows that a device that was originally planned for use in a purely manual assembly environment is completely unsuitable for use in a human-robot-collaboration on account of its geometry. The component's geometry results in sharp-edged contours, which in the very likely event of a hand being crushed between the device and the workpiece on the robot, would lead to collision pressures that significantly exceed the biomechanical limits for the hand area. Since these pressures cannot be adequately reduced by limiting the force and speed alone, the equipment has to be redesigned.

4. Profitability of HRC systems

Despite the great popularity of the topic of human-robot-collaboration in the context of Industry 4.0 and the, in principle, falling costs for the necessary hardware on account of the appearance of new suppliers on the robot market, a number of companies are still apprehensive of taking a step that could give them a cutting edge through the use of flexible, sensitive assistance robots.
One possibility for enterprises that as yet have no experience with automation technology in general and robot systems in particular is support through introductory projects organized by specialized service providers – in the field of risk analysis too – to ensure the success of a planned project. The reliance on external service providers declines with increasing practical knowledge, meaning follow-up projects can be realized even faster and at a lower cost.
Classic amortization calculations, the basis for investment decisions in most companies, come up against their limits with HRC applications. No valuation methods are usually available to determine the effects of the use of lightweight robots on productivity. What's more, it is also very difficult to quantify the positive side effects of improved work ergonomics, improved product quality and increased flexibility in terms of quantities in advance (5).

An exemplary calculation for the HRC assembly line at the TU Vienna pilot factory Industry 4.0 (see Fig. 20) shows the relevant calculation criteria. The use of the robot in addition to two members of staff can increase the daily production quantity by 25%, corresponding to an increase in production of 50,000 units over the system's service life. Although the total cost of ownership of the HRC assembly system is three times that of a classical, manual assembly line, almost 7.5% of the process costs per unit can nevertheless be saved through consistent personnel expenses, thanks to the increased output quantities in this assembly scenario – not to mention the positive ergonomic effects. It should be noted that this application is a demonstration scenario that focuses on investigating safety-relevant aspects. It has to be assumed that higher potential savings could be achieved through a specific optimization of the application with respect to economic efficiency.

Comparison of process costs:

	Manual assembly process	HRC assembly process
Useful life of the system [a]	5	5
Working days per year [d/a]	250	250
Daily operating hours of the system [h/a]	4	4
Costs of the system over the useful life [€]	€ 30.000	€ 90.000
Number of employees for the process	2	2
Labor costs [€/h]	€ 70	€ 70
Daily output [units]	160	200
Output over the useful life [units]	200.000	250.000
System costs [€/unit]	€ 0,15	€ 0,36
Labor costs [€/unit]	€ 1,75	€ 1,40
Process costs [€/unit]	€ 1,90	€ 1,76
Difference [%]		- 7,4

Fig. 20: Comparison of process costs for manual assembly process and HRC assembly process based on the assembly line in the TU Vienna pilot factory Industry 4.0

The costs per application can be reduced in particular by scaling and extending the use of HRC since some engineering expenses for identical or similar applications can be saved. In addition, increasingly intelligent and mobile robot systems can be used in a flexible way, thus raising their capacity utilization and spreading the costs associated with the system over a larger number of processes.

5. Perspective

The risk analysis method presented here as well as the measures to reduce risks in human-robot-collaboration that have been explained by way of example provide a good framework for the functionally safe design of HRC applications. If these methods are used in due time, companies also profit from a higher security of investments since the process can be designed safely and tailored to the employees' needs, thus making it ergonomic too, from the very outset .

They therefore constitute a key element of the integrated safety & security concept for human-robot-collaboration that has been developed in cooperation between TÜV AUSTRIA and Fraunhofer Austria Research, with JOANNEUM RESEARCH as an associated partner. The difficulties facing integrators and operators when dealing with standard specifications, above all in view of compliance with the biomechanical limits, are hereby addressed consistently.

The concept presented here does not yet take into account the role of human-robot-collaboration as a resource in a highly networked factory system. Initial investigations by TÜV AUSTRIA, however, already show that further risks arise if the HRC system is compromised on an IT level, risks that had not been considered in the former risk analysis process, or that measures taken to reduce the risks can be bypassed. In the next phase of the project, the potential ways in which HRC applications can be influenced as well as the exact manipulation possibilities will be investigated and determined in extensive penetration tests and system analyses, amongst other things. These findings will then be transferred to **the integrated safety & security concept** to allow an integrated risk analysis.

Further aspects of the research work will be the effects of increasing flexibility and product individualization within the scope of Industry 4.0, something that will also have a significant effect on the risk analysis and reduction process. This also affects mobile manipulators in particular, which can be used at changing locations and which may have to be able to handle processes at very short notice and temporarily.

The project partner will continue publishing the interim results from the development of the integrated safety & security concept on an ongoing basis and these will be placed at the disposal of interested companies and institutes.

About TÜV AUSTRIA

The Austrian TÜV is an international company with branch offices in more than 40 countries around the world and over 1,500 employees. The service spectrum ranges from machine safety and IT security, management systems certification, testing elevators and pressure equipment, plant safety, basic and further training, medical engineering, electrical engineering, technical environmental protection assessments, soundproofing assessments, carbon footprint evaluations, loss adjustments, app checks, all kinds of certifications and calibrations, product tests, technical due diligence and legal compliance checks, right through to tests of stage, photovoltaic and wind turbine systems.

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About Fraunhofer Austria Research

Fraunhofer is the biggest research organization for application-oriented research in Europe with over 24,000 employees. The research fields are based on human needs: health, safety, communication, mobility, energy and the environment. This is why the work of researchers and developers at Fraunhofer has a big effect on the future life of mankind.

They are creative, design technologies, develop products, improve processes and open up new paths. Around 50 employees work on projects in Austria, above all in the fields of production and logistics management as well as visual computing and in particular, the innovation of value-creation processes through emerging technologies.

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About JOANNEUM RESEARCH

JOANNEUM RESEARCH is a business-oriented innovation and technology provider that has been providing top-flight research on an international level for more than thirty years as part of an international network. The Institute for Robotics and Mechatronics (ROBOTICS) concentrates its research activity primarily on the safety of robot systems.

This specialist field covers both physical safety (Safety), cyber-safety (security) as well as safety-oriented artificial intelligence. In addition, research is carried out into topics such as human-robot-collaboration and interaction, mobile manipulation and intelligent automation in one of Austria's most up-to-date robot laboratories.

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