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***The EU Framework Programme for Research and Innovation H2020***
***Research and Innovation Action***

CENTAURO

# *Deliverable D8.1 CENTAURO Evaluation Concept*

**Dissemination Level: Confidential**

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| Project acronym: | CENTAURO |
| Project full title: | Robust Mobility and Dexterous Manipulation in Disaster Response by Fullbody Telepresence in a Centaur-like Robot |
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| Lead beneficiary: | LIU – Linköpings Universitet |
| Authors: | Giulia Meneghetti, Michael Felsberg, and Klas Nordberg |
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| 0.1 | 2015-08-28 | Giulia Meneghetti, Michael Felsberg and Klas Nordberg | Initial version for review within the consortium |
| 0.2 | 2015-09-18 | Giulia Meneghetti, Michael Felsberg and Klas Nordberg | Editing according the reviews from the partners: PGX, KTH and KHG. |
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**Executive Summary**

This deliverable reports the current status on the evaluation concepts used to assess the performance of the CENTAURO system as specified in Grant Agreement [8], reflecting the intention on how we believe the evaluation will be performed; it may be subject to changes since this is research work.
RoboCup Rescue [6], the DARPA Robotics Challenge [1] and the DLR SpaceBot Cup inspired test scenarios for navigation and manipulation tasks that will be reported in this deliverable. Performance matrics on the above scenarios will depend on a model defined by the complexity of the task and by the level of autonomy required by the task (Complexity Chain schema [7]).
This report includes an assessment of health and safety issues relating to testing and how they are dealt with, as well as informed consent procedures to be established for evaluation participants, like the main operator, along with sample information sheets and consent forms.
A multiple-stages approach will be adopted in order to evaluate the CENTAURO system and guide further research and development in the core work packages.
All the partners involved in the project will use the outcome of this deliverable, since it reflects what we believe is the course of action in the evaluation process of the CENTAURO system.

# Contents

# Abbreviations List

UBO - Rheinische Friedrich-Wilhelms-Universität Bonn

IIT - Italian Institute of Technology, Genova

SSSA - Scuola Superiore Sant'Anna, Pisa

KTH - Kungliga Tekniska Högskolan, Stockholm

LIU - Linköping University

RWTH - Rheinisch-Westfälische Technische Hochschule Aachen

PGX - progenoX GmbH, Bischofswiesen

KHG - Kerntechnische Hilfsdienst GmbH, Eggenstein-Leopoldshafen

IAB - International Advisory Board

NIST - National Institute of Standards and Technology

SaR - Search and Rescue

DRC - DARPA (Defense Advanced Research Projects Agency) Robotics Challenge

DLR - Deutsches Zentrum für Luft- und Raumfahrt

ASTM International - American Society for Testing and Materials International

CERTH - Centre for Research and Technology - Hellas (Greece)

# 1 Introduction

This deliverable reports on the evaluation concept to assess the performance of the CENTAURO system as specified in Grant Agreement [8], reflects the intention on how we believe the evaluation will be performed, but may be subject to changes since this is research work.

The objective of the deliverable is the development of systematic disaster-response benchmark scenarios and performance measures to asses the CENTAURO system. This is part of the “Requirement Specification and Evaluation” work package (Work Package 8). The partners primarily involved in the planning of the evaluation campaign (T8.1) are LIU, PGX, KHG.

Test scenarios and tasks have been identifies in this first part of the project, and then been discussed at the “Requirement Specification Workshop” at KHG on the 1st and 2nd of July 2015, by all partners (UBO, IIT, SSSA, KTH, LIU, RWTH, PGX, KHG, IAB) with the purpose to define tasks for the evaluation that will be performed on the CENTAURO system.

Testing scenarios for navigation and manipulation tasks are inspired by robot competitions and challenges, such as RoboCup Rescue [6], the DARPA Robotics Challenge [1], and the DLR SpaceBot Cup. The contribution of these challenges and the literature used to fulfil the objectives of this conceptual phase are described in Sec. 2. Input from professional rescue workers has been necessary to ensure the relevance of the test scenarios. The outcome of the conceptual phase reported in this deliverable will give a detailed description on the evaluation tasks and performance metric assessed (Sec. 3). This includes an assessment of health and safety issues relating to testing and how they are dealt with, as well as informed consent procedures to be established for evaluation participants, like the main operator, along with sample information sheets and consent forms.

A multiple-stage approach will be adopted in order to guide the further research and development in the core work packages. In the first stage (milestone 2) core components will be evaluated in a test arena following the procedures developed by the US National Institute of Standards and Technology (NIST)(Fig. 1). In the second and third stages (milestones 3 and 4) the whole system will be evaluated in a test facility for physical emulation of Search and Rescue (SaR)(Fig. 2). A detailed implementation plan for evaluation is presented in Sec. 5.

All the partners involved in the project will use the outcome of this deliverable, since it reflects what we believe is the course of action in the evaluation process of the CENTAURO system and its core components.

Figure 1: NIST metrics for evaluating response robots. **Left:** Arena for testing mobility. **Right:** Manipulation task.

# 2 Related Work

Based on the input from end-users, a set of systematic disaster-response benchmark scenarios and performance measures will be developed to assess the CENTAURO system. The assessment will be performed at two integration milestones in the third and fourth year of the project, with increasing level of complexity of the tasks in test scenarios [7]. The tasks will be inspired by robot competitions and challenges, such as RoboCupRescue [6] and the DARPA Robotics Challenge [1]. We will collaborate closely with professional rescue workers to ensure the relevance of the test scenarios. The evaluation will be first carried out in the virtual testbed (physics-based simulation of the robot and its environment), then in specifically constructed benchmark arenas, as well as in realistic training facilities of professional rescue workers. All available data will be captured and analysed to assess task performance, operator work load, sensitivity to communication problems, and for finding the root causes of failures.

## 2.1 First stage: Standard Test Methods for Evaluating Specific Capabilities

In this stage, we will use the testing arenas from the US National Institute of Standards and Technology (NIST) and RoboCup Rescue, which are offering a valuable testbed to quantitatively evaluate the skills of the robot of the CENTAURO system in traversing rough terrain (Fig. 1 **Left**). These arenas offer terrain types of increasing difficulty, namely the *orange arena* containing moderate terrains with crossing 15 degrees pitch-and-roll ramps and structured obstacles such as stairs and inclined planes, and the *red arena* consisting of complex terrains made of wooden stepfields requiring advanced robot mobility. Additionally, we will utilize the *blue arena* metric for assessing the robot's capability of mobile manipulation when situated on non-flat terrain, and to place simple blocks or bottle payloads carried in from the start or picked up within the arenas (Fig. 1 **Right**). These were documented in detail and published by the ASTM International [5].

## 2.2 Second and Third stage: Usability benchmark

Usability estimates are a good method for benchmarking robotic systems when the interaction between the system and the human operators plays an important role, like in the CENTAURO system. To this end, we intent to utilize testing environments similar to those presented at the DARPA Robotics Challenge (DRC) [1]. For example, it is planned to consider a similar terrain testing course as described by DRC task 2 and a similar debris testing course as described by DRC task 4 (Table. 1).

A final demonstration of the CENTAURO system could be conducted e.g. in a test facility of the German fire brigade designed for physical emulation of Search and Rescue (SaR) scenarios, called Ahrweiler USAR (Fig. 2, Fig. 3 and Fig. 4) testing facility that is used for training of blue-light response forces. This site is a good compromise between the need for standardization in benchmarking procedures and the inevitable differences in the variety of robotic systems and applications (or even tasks). In the literature, usability is estimated through the evaluation of several different indices, but the most widely used are SA (Situational Awareness) and WL (Work Load). Situational Awareness is a good index for both efficiency and effectiveness of a system, independently of the specific features of a platform, a GUI or in general a robotic tele-presence system.

Table 1: DARPA robotics challenge tasks and description

| DRC Tasks | Brief Description | CENTAURO relevance |
|---|---|---|
| Task 1 | Vehicle : The Vehicle task consists of two sub-tasks: (1) Robot drives the vehicle through the course, and (2) Robot gets out of the vehicle and travels dismounted out of the end zone. | no |
| Task 2 | Terrain : The Terrain task consists of three sub-tasks: (1) Traverse initial terrain segment, (2) Traverse middle terrain segment and (3) Traverse final terrain segment. | yes |
| Task 3 | Ladder : The Ladder task consists of three sub-tasks: (1) All contact points on or above the first step, (2) All contact points on or above the fourth step and (3) No contact points below the landing. | no |
| Task 4 | Debris : The Debris task consists of three sub-tasks: (1) Remove five pieces of debris, (2) Remove an additional five pieces of debris, and (3) Travel through the open doorway. | yes |
| Task 5 | Door : The Door task consists of three sub-tasks: (1) Enter push door, (2) Enter pull door, and (3) enter pull door with weighted closer. | yes |
| Task 6 | Wall : The Wall task consists of cutting a predefined shape on a wall. | no |
| Task 7 | Valve: The Valve task consists of three sub-tasks: (1) Close a first valve, (2) Close a second valve and (3) Close a third valve. | yes |
| Task 8 | Hose : The Hose task consists of three sub-tasks: (1) Hose nozzle moves past the yellow line, (2) Hose nozzle touches the wye and (3) Hose nozzle attaches to wye. | yes |

Figure 2: Ahrweiler USAR testing facility.

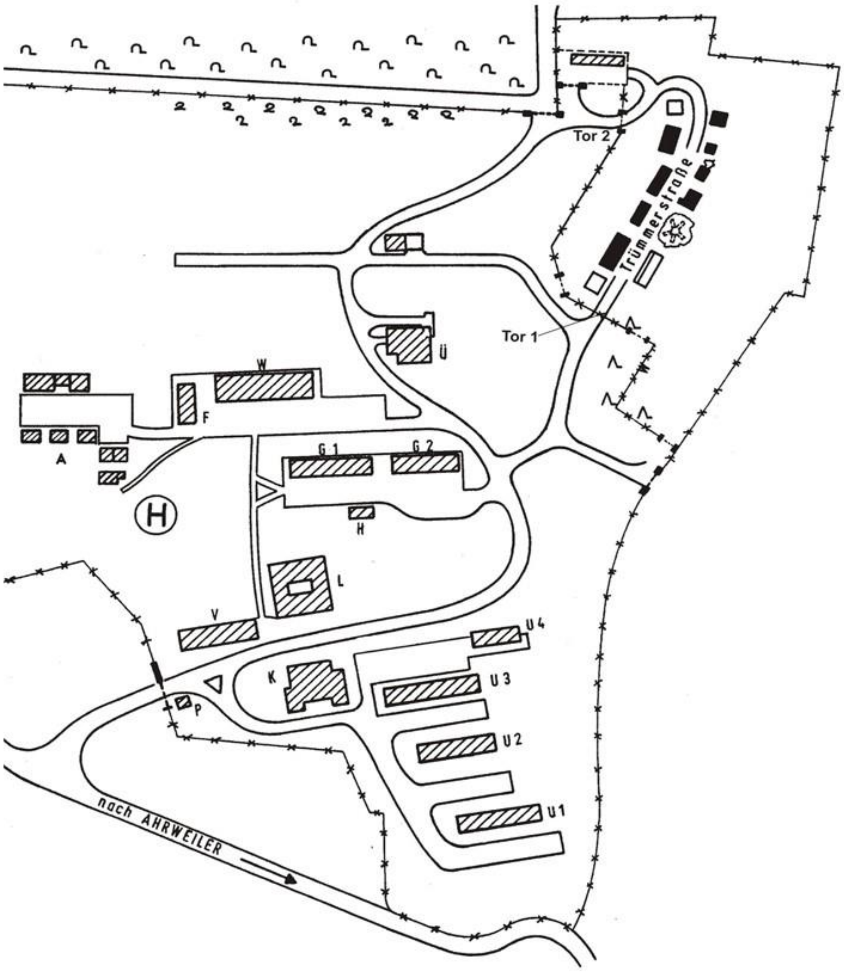


Figure 3: Schematic map of the Ahrweiler USAR testing facility, overview.

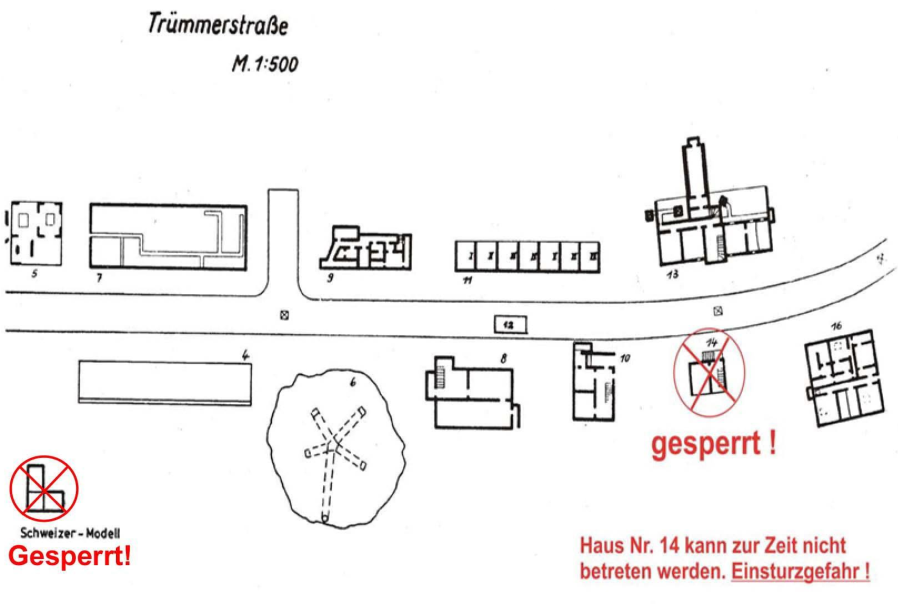


Figure 4: Schematic drawing of the Ahrweiler USAR testing facility, “Trümmerstraße”

SA can be measured both on the local and remote environment, but for the CENTAURO project it will only be estimated for the remote environment, because the Human-Machine Interaction (HMI) is immersive. Therefore, by definition it neglects the local SA in favor of remote SA. This approach can be used because the operator works from a safe position. Hence, the operator is not required to maintain a high level of SA on the local environment. SA can be estimated at three different levels:

- Data level: availability of remote data to the operators (of both system and environment),
- Comprehension level: interpolation of available data and of possible consequences (for example danger of overheating or low batteries),
- Projection level: inference of future events (for example imminent collision, or choice of traversable path). Many quantitative methods have been proposed for the measure of SA, among which the most relevant, and suitable for the CENTAURO scenario are:
  1. SAGAT (Situation Awareness Global Assessment Technique) [3]: direct interrogation of the subject during operation for the estimation of mental state (non-usable in real environments); can be used in simulation, and in the design phase for the design of the Control Station and GUI.
  2. Lasso [2] : based on the estimate of five aspects relevant for the SA, namely: Location: awareness of the mobile platform position with respect to a known reference; Activities: awareness of the progress of the ongoing task surroundings; awareness of the obstacles along the path; Status: awareness of the mobile platform operational status (diagnostic); Overall Mission: awareness of the overall mission progress, including the contribution of other agents, when available. Lasso uses a "think aloud" procedure, i.e., the operators are encouraged to express comments on the previous aspects while performing the task.

Operator Workload is another important metric for usability. It can be defined as the cost in terms of stress, frustration and mental effort, required to accomplish a mission. It can be estimated based on objective parameters, subjective parameters, or performance parameters. Objectives parameters consist of biometric measures (when available) like blood pressure, EDA (electrodermal activity), EMG (electromyography), HRV (heart rate variation), or eye tracking. Subjective parameters are opinions of the operators expressed by numerical marks of some operational parameters related with workload. Performance parameters are indirect measures of workload derived by the ranking of the task performance. A very common method for the WL measure is the NASA Task Load Index [4]. It belongs to the subjective parameters class, and it consists in a synthetic measure (a single number score) derived by a weighted average of several key parameters related with the workload. These parameters are evaluated with an interview presented to the operator, immediately after completion of a task.

# 3 Evaluation Concept

The RoboCup Rescue challenge [6], the DARPA Robotics Challenge [1] and the DLR SpaceBot Cup have inspired the testing scenarios for navigation and manipulation tasks that will be employ in the CENTAURO system. Both the tasks and evaluation metric to assess the performance of the CENTAURO system have been discussed by all the consortium in the "Requirement Specification Workshop" at KHG in July 2015.

The proposed scenarios follow a complexity chain schema [7]. It allows for an efficient learning process in a similar fashion to that used in biological system and can also be used as a method for evaluating a cognitive system's performance. This approach will be used for the evaluation of the CENTAURO system by increasing the level of complexity of the test scenarios for locomotion and manipulation tasks.

## 3.1 Locomotion

The CENTAURO system will be evaluated in a multi-stage approach. In month thirty [M30], the system will be evaluated on basic locomotion tasks: walking over ramps with a inclination of 30 degrees, overcoming gaps of 30 cm length and climbing regular straight stairs. The capability of the robot to change direction when landing at the top of the staircase will be evaluated.

Other tasks that will be performed by CENTAURO ([M30]) concern walking over obstacles and rough terrain, which will be perform in the RoboCup Rescue 3D step field (Fig. 1), and passing through doors. The notion of "door" has been discussed, since there exist a lot of different types of doors with different handles and locking systems. For the first step of the evaluation [M30], the robot will be evaluated while walking through "Regular doors" (Heigh:180 cm, Width: 70 cm) with a handle and not locked. In the final stage of the evaluation [M42], the CENTAURO system will try to pass through a regular locked door, provided with a weighted-closer mechanism (Fig. 5). This will evaluate another aspect of the CENTAURO: performing a combination of a locomotion and a manipulation task. Moreover, all the previous tests scenarios will increase their complexity: adding movable object (debris), for the obstacles and the stairs climbing tasks, as well as increasing the slope and the gap for the respective challenges. A brief description of the tasks has been summarize in Table 2.

Table 2: Locomotion Tasks

| Taks | [M30] | [M42] |
|---|---|---|
| Door | "Regular door" opening and going through a regular door with a handle, unlocked | Add closing mechanism and use key to unlock |
| Obstacles | RoboCup Rescue 3D step field | Add debris on the field |
| Stairs | Regular stairs, straight, change direction when landing at the top | Add debris on the stairs |
| Ramp | 30 degrees | 45 degrees |
| Gap | 30 cm | 60 cm |

Figure 5: Weighted-closer system mounted on a door. Passing through the door will require the ability to keep it open while moving through.

### 3.2 Manipulation

A set of manipulation tasks related to disaster-response environments has been selected for evaluating the manipulation capabilities of the CENTAURO system (Table 3). In the first stage of the evaluation of the integrated system [M30] the robot will be evaluated primarily on single-hand tasks. Snap hook (Fig. 6), use a drill and a power screw-driver (with the screw already partially in the wood), cutting a fire hose or a fixed pipe (maximum diameter of 20 cm) and try to connect a fire hose to its stationary part will also be part of the evaluation. In the final stage of the evaluation [M42], the robot will be evaluated on more difficult versions of the previous tasks, that will involved the use of a second hand. The drill will be larger and the cable to fix

Table 3: Manipulation Tasks

| Tasks | [M30] | [M42] |
|---|---|---|
| Turn valve | Different locations, different diameters | Put uneven ground in front of it |
| Pipe Stars | | Inspection, direction, extraction and insertion |
| Fire hose connection | Connect mobile hose to stationary part | Connect two hoses (both mobile) |
| Power connection | Connect plug to stationary part 230V | Connect plug to a part (both mobile) 230V, 400V |
| Take a sample | Follow a surface with a sensor | Smear test |
| Fix a cable | Snap hook | Shackle |
| Use a power screw driver | Screw is already partially in the wood | Attach a piece of wood to some static wood |
| Use a drill | Single-handed | Two -handed larger version |
| Cut max 20 mm diameter cable or pipe | Use a cutting tool | Secure the part that is being cut off with the second hand |

Figure 6: **Left:** Snap hook. **Right:** Shackle.

Figure 7: The upper power cord has three pins (230V) the lower power cord five pins (400V)

will require the use a shackle (Fig. 6). Both the cutting of a fire hose or of a fixed pipe will require the use of two hand if the two extremities will not be fixed.

Power connection tasks will be considered because electric power in various missions is needed to perform manipulation tasks. The first stage of evaluation of the integrated CENTAURO system will include a task to connect a power cord to a stationary socket of 230V (see Fig. 7 for an example of how it looks). In the last step, both sockets are mobile to increase the complexity of the task and two different type of them (230V and 400V, Fig. 7) will be tested.

The CENTAURO system will be also evaluated responding the capability to inspect, direct, extract and insert a pipe star (Fig. 8). A Smear test will be a further task for evaluating the precision of the CENTAURO system [M42]. A defined surface (300 $cm^2$) will be wiped with a special test paper (circular shape, diameter about 5 cm). The paper has one adhesive side and can easily be grasped by the manipulator using a specific adapter. This task requires high precision, which is why the corresponding initial evaluation task will be of trying to follow a surface at a certain distance.

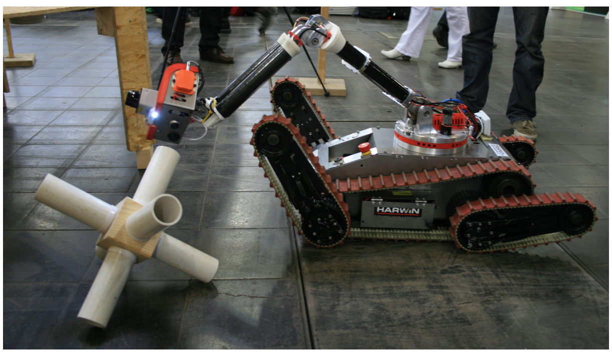

Figure 8: Pipe Star

## 3.3 Performance Measure

A measure on the performance (score) of the CENTAURO system on the above tasks has to be computed. This score will depend on a normalized model defined by the complexity of the task and by the level of autonomy required by the task (Fig. 9). This shows that we expect higher score when complexity and autonomy level decrease. The initial intention is to not aim to full autonomy, but only to introduce autonomy at a certain low-level capabilities of the CENTAURO system. The primary focus on this evaluation will be on the case when the robot is fully remotely controlled by the operator, but later on in the project some low-level capabilities may be extended to increase autonomy.

For statistical evidence every task will be repeated and normalized (the changing level of experience of the operator will be compensated) to achieve an unbiased distribution of the score, can be used to describe the behaviour of the system and to guide further research. The variety of tasks and test scenarios imposes different ways of defining the success of performance:

1. Graded metric: the score represents the measure of success on the performance in a scale labelled from failure to full success.

2. Binary metric: the score is a binary measure, which represents either a failure or a success of the tasks.

Another important aspects of the score estimation is time to execute a task. When a task has been accomplished (or performed successfully), the execution time will be used to assess the performance of the CENTAURO system.

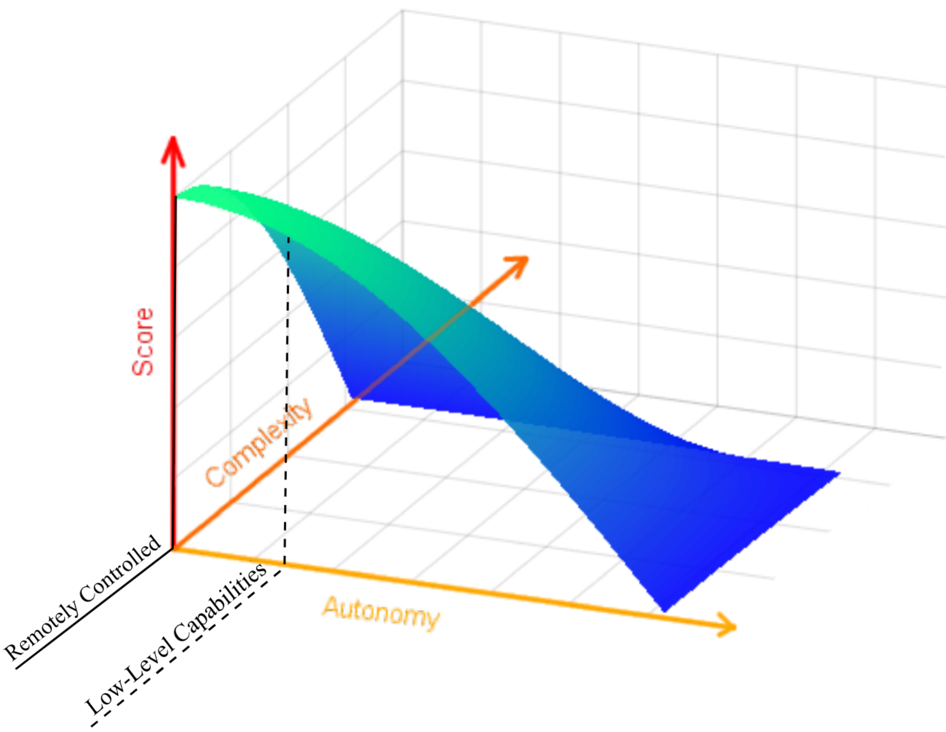


Figure 9: The figure shows the general model that will be used in the computation of the score. The primary focus is to evaluate the system when it is fully remotely controlled by the operator (black line). Later on in the project some low-level capabilities may be extended to increase autonomy (dashed line).

## 3.4 Progress in CENTAURO beyond the State-of-the-Art

In addition to the use of established benchmark and performance measures, CENTAURO will develop a set of systematic disaster-response benchmark scenarios and performance measures beyond the State-of the-Art, to assess the development of symbiotic human-robot systems and individual components of it. Evaluation will start with core components after the first year, continue with simple navigation and manipulation tasks for the first integrated system in the third year [M30], and finally evaluate the full functionality required for disaster response tasks in the fourth year [M42]. The results of the intermediate evaluations will guide the further research and development in the core work packages. The development of the CENTAURO system will guide research to improve functionalities requiredto face future disaster-response scenarios.

# 4 Health and Safety issues

During the system development, health and safety recommendations and procedure has to be followed. An example of safety guides to follow can be found in the Appendix at the end of the document, from Adept Robot which deal with robot safety.

The formulation of safety instructions for the CENTAURO system will take into account the safety requirements for collaborative robots and application reported in Table 4. They have been proposed in the workshop: " Workspace Safety in Industrial Robotics: trends, integration and standards" in 2014 organized by ABB Corporate Research (see Appendix).

It is the responsibility of an assigned "Robot Operation Officer" who is on-site to check that safety instructions are fulfilled. Participating researchers that perform experiments, must sign a consensus form. A draft of the CENTAURO consensus form based on a regulation form from CERTH can be found in the Appendix.

It will require modifications from the responsible person of the respective site, and possible a legal advisor. The final formulation of the consensus form will be provided by the owner of the site or the responsible person of the site latest three months ahead of the experiments.

Table 4: Some safety standards and directives for collaborative robots and applications from the Industrial Safety Requirements for Collaborative Robots and Applications Workshop from ABB Corporate Research, 2014-03-10

| Standards and Directives | Description |
|---|---|
| ISO 10218-1 | Robots and robotics devices (industrial use, controller, manipulator, collaborative application scenarios) |
| ISO 10218-2 | Robot system/cell (robot, tooling, work pieces, periphery, safeguarding) |
| ISO 11161 | Integrated manufacturing systems (for applications of Industrial Robots) |
| ISO 13849-1 / IEC 62061 | Safety related parts of control systems (for applications of Industrial Robots) |
| IEC 60204-1 | European Machinery Directive (for applications of Industrial Robots) |
| IEC 61508 | Functional Safety (for applications of Industrial Robots) |
| ISO 12100 | Risk Assessment (for applications of Industrial Robots) |
| ISO 13850 | E-stop (Safety Functions of Industrial Robot Controller) |
| IEC 60204-1 | Electrical equipment, protective stop: stop categories (cat. 0, cat. 1, cat. 2) (Safety Functions of Industrial Robot Controller) |

# 5 Implementation Plan

The evaluation of the CENTAURO system will take place in multiple stages. All evaluation tasks will be carried out in the Virtual Testbed. At the first stage we will evaluate core components using the NIST standard performance metrics [6]. A risk analysis on the performed tasks will be conducted. PGX will monitor and will generate a list, displaying the planned trainings and exhibitions for 2016 among search and rescue services. New option for evaluation will be considered based on this list. The second stage will take place at Ahrweiler-USAR (Fig. 2). At this stage, only a preliminary version of the system will perform basic tasks, involving, for example, single-arm manipulation. The third and final stage will take also place at Ahrweiler-USAR (Fig. 2), with the complete system for the test of the full functionality. Each evaluation stage will include the tasks planned in Sec. 3. As we see in Table 5 the next stage will required

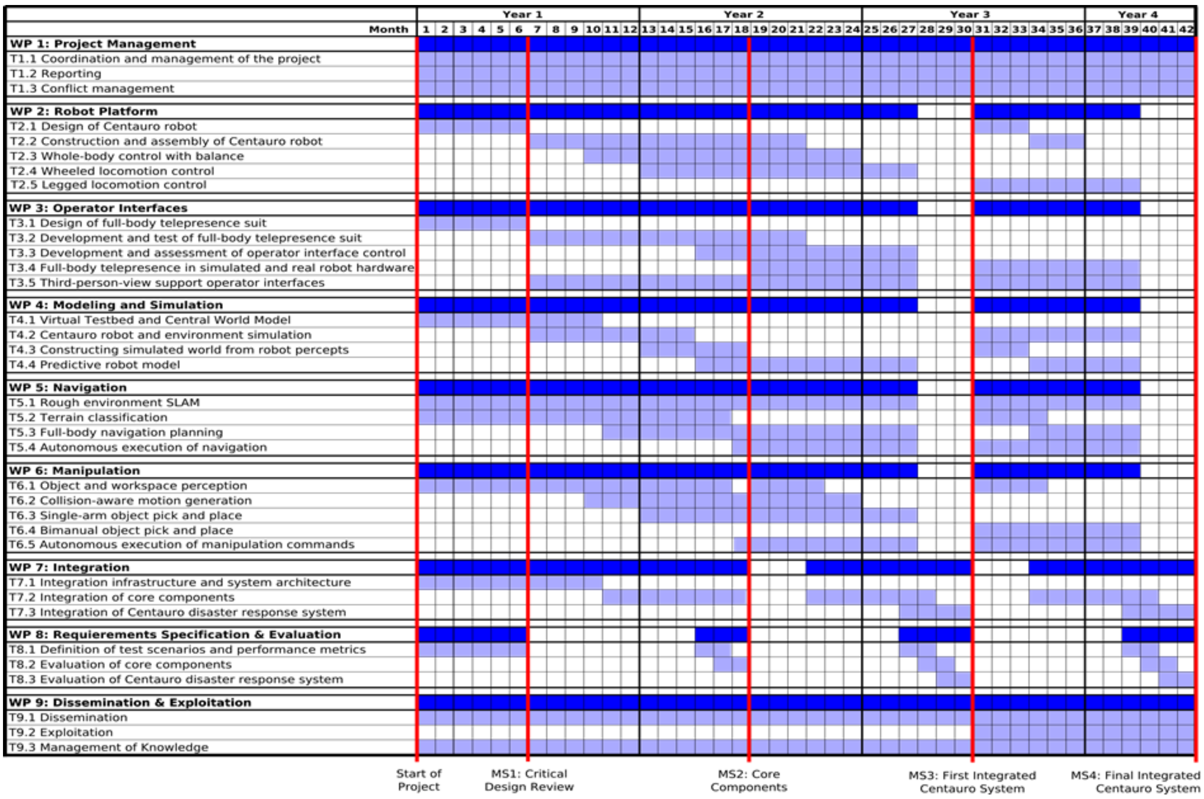


Figure 10: Gantt diagram summarizing all the milestone.

the evaluation of the core components for every work packages after the first year (M15-M17), go over relatively simple navigations and manipulations tasks for the first integrated system after the second year (M27-M30), to the full functionality required for disaster response tasks after the third year (M39-M42). The results of the intermediate evaluations will guide the further research and development in the core work packages.

An example on how this evaluation can be conducted, has been reported from the deliverable D5.1 on Navigation concept (see Table 6). It proposes a stage procedure on the acquisition of the dataset that will be used in the process of the evaluation of the navigation module. Initially, simulation data will be used, then publicly available dataset will be found in relation to the CENTAURO project application. If needed locally produced data will be generated. Later on, data from the sensors without being mounted on the robot will be collected and as a final step the data from the full setup will be uses. However, the first core components evaluation performed is subject to the responsibility of the respective work packages.

Table 5: Summary of the procedure steps relevant for the evaluation plan.

| Procedure | Description |
|---|---|
| P2 | Core Component Development (M7-M17). Core system will be developed and individually validated at MS2. |
| P3 | First system Deelopment (M18-30). The first CENTAURO system with partial functionality will be integrated and evaluated in simplified scenarios at MS3. |
| P4 | Final system development (M31-42). The final CENTAURO system with full functionality will be developed, integrated, and evaluated in realistic scenarios at MS4. |

Table 6: Stepwise procedure for data acquisition and usage of the core components of the CENTAURO system. (This Table has been copied from the deliverable 5.1 on Navigation concept).

| What | When | From Whom | Nature |
|---|---|---|---|
| Existing sensor data similar to CENTAURO data | M6 | UBO | RGBD |
| Existing sensor data via Central World Model (CWM) | M8 | RWTH | RGBD |
| Local (as in the partner) data for local test | on demand | all | varies |
| Real data from CENTAURO sensor (not on final system) | M12 | IIT | |
| Real data from CENTAURO sensor via CWM | M14 | RWTH | |
| Real data from CENTAURO system | M30 | IIT | |
| Real data from CENTAURO system via CWM | M30 | RWTH | |

# 6 Conclusions

This deliverable has reported the current status on the evaluation concepts used to assess the performance of the CENTAURO system as specified in Grant Agreement [8], reflecting the intention on the evaluation will be performed; it may be subject to changes since this is a research work. RoboCup Rescue [6], the DARPA Robotics Challenge [1] and the DLR SpaceBot Cup have inspired the testing scenarios for navigation and manipulation tasks described in this deliverable. Both the tasks and evaluation metric to assess the performance of the CENTAURO system have been discussed by all the consortium in the "Requirement Specification Workshop" at KHG in July 2015.

The proposed scenarios follow a complexity chain schema by increasing the level of complexity of the test scenarios for locomotion and manipulation tasks in the evaluation. A measure on the performances (score) on the above tasks will depend on a model defined by the complexity of the task and by the level of autonomy required by the task. This general model is limited to certain low-level autonomous capabilities in case of the CENTAURO system.

An assessment of health and safety issues relating to testing and how they are dealt with, as well as informed consent procedures to be established for evaluation participants, like the main operator, along with sample information sheets and consent forms is included.

A multiple-stages approach will be adopted in order to guide the further research and development in the core work packages. In the first stage (milestone 2) core components will be evaluated in a test arena following the procedures developed by the US National Institute of Standards and Technology (NIST)(Fig. 1). In the second and third stages (milestones 3 and 4) the whole system will be evaluated in a test facility for physical emulation of Search and Rescue (SaR)(Fig. 2).

All the partners involved in the project will use the outcome of this deliverable, since it reflects what we believe is the course of action in the evaluation process of the CENTAURO system and its core components.

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# Appendix

- Adept Safety guide PDF
- Industrial Safety Requirements for Collaborative Robots and Applications
- Robot rules and regulation form

# Adept Robot

## Safety Guide


11185-000 Rev. A
December, 2011

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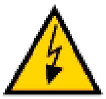
Created in the United States of America

# Table of Contents

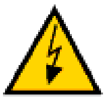
# Chapter 1: Alert Notation

There are six levels of alert notation used in Adept manuals. In descending order of importance, they are:



**DANGER:** This indicates an imminently hazardous electrical situation which, if not avoided, will result in death or serious injury.

**DANGER:** This indicates an imminently hazardous situation which, if not avoided, will result in death or serious injury.



**WARNING:** This indicates a potentially hazardous electrical situation which, if not avoided, could result in serious injury or major damage to the equipment.

**WARNING:** This indicates a potentially hazardous situation which, if not avoided, could result in serious injury or major damage to the equipment.

**CAUTION:** This indicates a situation which, if not avoided, could result in minor injury or damage to the equipment.

**NOTE:** Notes provides supplementary information, emphasizes a point or procedure, or gives a tip for easier operation.

# Chapter 2: Fixed Robots

## 2.1 Definition

An industrial robot is an automatically controlled, programmable, multi-purpose, manipulative machine with several degrees of freedom, for use in industrial automation applications. It may be either fixed in place or mobile.

## 2.2 Compliance and Intended Use

### Compliance

The installation and use of Adept products must comply with all safety instructions and warnings in this guide and any user or reference guides for the equipment. Installation and use must also comply with all applicable local and national requirements and safety standards.

### Intended Use

Adept equipment is not intended for use in any of the following situations:

- In hazardous (explosive) atmospheres
- In life-support systems
- In residential installations
- Where the Adept equipment will be subject to extremes of heat or humidity.

**CAUTION**: The instructions for operation, installation, and maintenance given in this guide and the robot user's guide must be strictly observed.

Non-intended use of Adept equipment can:

- Cause injury to personnel
- Damage the robot or other equipment
- Reduce system reliability and performance

All persons that install, commission, operate, or maintain the robot must:

- Have the necessary qualifications
- Read and precisely follow the instructions in this safety guide
- Read and precisely follow the instructions in the robot user's guide

If there is any doubt concerning the application, ask Adept to determine if it is an intended use or not.

## 2.3 Risk Assessment

Safety standards in many countries require appropriate safety equipment to be installed as part of the system. Safeguards must comply with *all* applicable local and national standards for the location where the robot is installed.

Adept has performed Risk Assessments for Adept robots, based on the intended applications of the robot. The conclusions are summarized below

### Exposure

When Arm Power is on, all personnel must be kept out of the robot workcell by interlocked perimeter barriers. It is up to the customer to determine if teaching the robot in Manual Mode, by a skilled programmer (see See "Qualification of Personnel"), wearing safety equipment and carrying an Adept pendant, is allowable under local regulations.

### Severity of Injury

Provided that skilled personnel who enter the robot workcell are wearing protective headgear, eyeglasses, and safety shoes, it is likely that injuries caused by the robot would be slight (normally reversible). The risk of severe injury increases as the size of the robot and payload increase.

### Avoidance

If the customer determines that teaching the robot in Manual Mode is allowable, the programmer must always carry the pendant when inside the workcell, as the pendant provides both E-Stop and Enabling switch functions.

For *normal* operation (AUTO mode), user-supplied interlocked guarding must be installed to prevent any person entering the workcell while Arm Power is on.

**DANGER**: The robot system must be installed with user-supplied interlock barriers. The interlocked barriers must open the E-Stop circuit in the event of personnel attempting to enter the workcell when Arm Power is enabled. Failure to install suitable guarding or interlocks could result in injury or death.

The following circuits are all dual channel, and classified as category 3, PL-d:

- Front panel
- Adept Pendant
- Safety door (mute gate)
- External (user or line) E-Stop

The Risk Assessment for *teaching* an Adept product depends on the application. If the customer determines that teaching the robot in Manual Mode is allowable, the programmer may need to enter the robot workcell while Arm Power is enabled. Other programming methods can be used so that the programmer does not have to enter the workcell while Arm Power is on.

Examples of alternative methods of programming include:

- Programming from outside the safety barrier
- Programming with Arm Power off
- Copying a program from another (master) robot
- Off-line or CAD programming

### Safety System Behavior

The standard control system is fully-hardened to all EMI influences. In addition, a software-based reduced-speed mode has been incorporated to limit speed and impact forces on an Operator and production tooling when the robot is operated in Manual Mode.

## 2.4 Transportation

Always use adequate equipment to transport and lift Adept products. See the Installation chapter of the robot user's guide for more information on transporting, lifting, and installing.

## 2.5 Safety Barriers

**CAUTION**: Adept Technology strictly prohibits installation, commissioning, or operation of an Adept robot without adequate safeguards. These must be compliant with applicable local and national standards.

Safety barriers must be provided that prevent personnel from entering the workcell whenever power is applied to the equipment. Adept systems are computer-controlled and may activate remote devices under program control at times or along paths not anticipated by personnel. It is critical that safeguards be in place to prevent personnel from entering the workcell whenever power to the equipment is present.

The user must ensure that adequate safeguards, safety barriers, light curtains, safety gates, safety floor mats, etc., are installed. The robot workcell must comply with applicable local and national standards.

The height and the distance of the safety barrier from the robot must ensure that personnel cannot reach the work envelope of the robot.

**CAUTION**: Never remove any safeguarding and never make changes in the system that will decommission a physical safeguard.

The Adept control system has features that aid the user in constructing system safeguards, including customer emergency-stop circuitry and digital input and output lines. The emergency power-off circuitry is capable of switching external power systems and can be interfaced to the appropriate user-supplied safeguards. See the Adept SmartController User's Guide for additional information.

### Impact and Trapping Points

Adept robots are capable of moving at high speeds. If a person is struck by a robot (impacted) or trapped (pinched) serious injury could occur. Robot configuration, joint speed, joint orientation, and attached payload all contribute to the total amount of energy available to cause injury.

### Hazards from Expelling a Part or Attached Tooling

Any tooling, fixtures, end-effectors, etc., mounted to the tool flange, or one of the other axes of the robot, must be attached by sufficient means to resist being expelled from the robot. Additionally, any payload must be held by the end-effector in a manner that prevents the payload from being expelled accidentally.

The safety barrier constructed around the robot must be designed to withstand the impact of any item expelled accidentally from the robot. Projectile energy can be calculated using the formula $E = \frac{1}{2}mv^2$.

**NOTE**: In the Projectile energy formula above:

E = Energy

M = Mass

V = Velocity

## 2.6 Robot Modifications

It is sometimes necessary to modify the robot in order to successfully integrate it into a workcell. Unfortunately, many simple modifications can either cause a robot failure, or reduce the robot's performance, reliability, or lifetime. The following information is provided as a guideline to modifications.

### Acceptable Modifications

In general, the following robot modifications do not cause problems, but may affect robot performance:

- Attaching tooling, utility boxes, solenoid packs, vacuum pumps, cameras, lighting, etc., to the robot tool flange
- Attaching hoses, pneumatic lines, or cables to the robot

  These should be designed so they do not restrict joint motion or cause robot motion errors.

### Unacceptable Modifications

**CAUTION**: For safety reasons, it is prohibited to make certain modifications to Adept robots.

The modifications listed below may damage the robot, reduce system safety and reliability, or shorten the life of the robot. The warranty of the entire robot, or certain parts, may be voided.

**CAUTION**: Making any of the modifications outlined below voids the warranty of any components that Adept determines were damaged due to the modification. You must contact Adept Customer Service if you are considering any of the following modifications:

- Modifying any of the robot harnesses or robot-to-controller cables
- Modifying any robot access covers or drive system components
- Modifying, including drilling or cutting, any robot surface
- Modifying any robot electrical component or printed-circuit board
- Routing additional hoses, air lines, or wires through the inside of the robot
- Modifications that compromise EMC performance, including shielding

## 2.7 Installation

### General Precautions

Take precautions to ensure that the following situations do not occur:

- Improper installation or programming of the robot system
- Use of non-Adept supplied cables or modified components in the system

### Safety Requirements for Additional Equipment

- Additional equipment used with the Adept robots (grippers, conveyor belts, etc.) must not reduce the workcell safeguards
- Emergency stop switches must be accessible at all times.
- All components in the robot workcell must comply with all local and national safety requirements

## 2.8 Operation

This guide and the robot user's guide must be read by all personnel who install, operate, or maintain Adept systems, or who work within or near the workcell.

A moving robot arm can cause serious injury.

- Do not enter the safety fence during automatic operation
- Push the emergency stop button before entering the workcell
- Do not defeat any aspect of the safety E-Stop system
- Do not defeat an interlock so that an operator can enter a workcell with High Power ON
- Take precautions to prevent ejection of a work piece (See "Hazards from Expelling a Part or Attached Tooling ")

Adept robots have a Manual and an Automatic (AUTO) operating mode. While in Automatic Mode, personnel are not allowed in the workcell.

If the customer determines that teaching the robot in Manual Mode is allowable under local regulations, operators with additional safety equipment may work in the robot workcell. For safety reasons the operator should, whenever possible, stay outside of the robot workcell to prevent injury. The maximum speed and power of the robot is reduced, but it could still cause injury to the operator.

The type of safety equipment required for operators working within a workcell must be determined by the user, based on industry standards and their installation. Safety glasses, protective headgear (hard hat), and safety shoes are examples to be considered.

Warning signs must be posted around the workcell to ensure that anyone working around the robot system knows they must wear safety equipment.

## Qualification of Personnel

This guide assumes that all personnel have attended an Adept training course and have a working knowledge of the system. The user must provide the necessary additional training for all personnel who will be working with the system.

As noted in this guide, certain procedures should be performed only by skilled or instructed persons. For a description of the level of qualification, Adept uses the standard terms:

- **Skilled persons** have technical knowledge or sufficient experience to enable them to avoid the dangers, electrical and/or mechanical
- **Instructed persons** are adequately advised or supervised by skilled persons to enable them to avoid the dangers, electrical and/or mechanical

All personnel must observe industry-prescribed safety practices during the installation, operation, and testing of all electrically-powered equipment. To avoid injury or damage to equipment, always remove power by disconnecting the AC power from the source before attempting any repair or upgrade activity. Use appropriate lockout procedures to reduce the risk of power being restored by another person while you are working on the system.

**WARNING**: Before working with the robot, every entrusted person must confirm that they:

- Have received the guides (both this guide, and the robot user’s guide)
- Have read the guides
- Understand the guides
- Will work in the manner specified by the guides

## Protection Against Unauthorized Operation

The system must be protected against unauthorized use. The user or operator must restrict access to the keyboard and the pendant by locking them in a cabinet or using another adequate method.

## 2.9 Sound Emissions

The sound emission level of the Adept robots depends on the speed and payload. The maximum value is 90 dB. (This is at maximum AUTO-mode speed.)

**WARNING**: Acoustic emission from this robot may be up to 90 dB (A) under worst-case conditions. Typical values will be lower, depending on payload, speed, acceleration, and mounting. Appropriate safety measures should be taken, such as ear protection and display of a warning sign.

## 2.10 Thermal Hazard

The following warning applies to both the base and outer link for Adept Cobra robots. It applies to the base for the Adept Quattro robot, and all links for Adept Viper robots.

**WARNING**: You can burn yourself. Do not touch the robot after it has been running at high ambient temperatures (40-50° C, 104-122° F) or at fast cycle times (over 60 cycles per minute). The robot skin/surface temperature can exceed 85° C (185° F).

## 2.11 Maintenance

Before performing maintenance in the workcell of the robot, High Power must be switched off and the power supply of the robot must be switched off and locked and tagged out. After these precautions, a skilled person is allowed to perform maintenance on the robot.

Only skilled persons with the necessary knowledge about safety and operating the equipment are allowed to maintain the robot system.

**CAUTION**: During maintenance and repair, the power of the Adept equipment must be turned off. Lockout measures must be used to prevent unauthorized personnel from turning on power.

## 2.12 Risks That Cannot Be Avoided

The Adept control system includes devices that disable High Power if a system failure occurs. However, certain residual risks or improper situations could cause hazards. The following situations may result in risks that cannot be avoided:

- Failure of software or electronics that may cause high-speed robot motion in Manual Mode
- Failure of hardware associated with an enabling device or E-Stop system

## 2.13 What to Do in an Emergency Situation

Press any E-Stop button (a red push-button on a yellow background/field) and then follow the internal procedures of your company or organization for an emergency situation. If a fire occurs, use $CO_2$ to extinguish the fire.

# Chapter 3: Mobile Robots

## 3.1 Definition

An industrial robot is an automatically controlled, programmable, multi-purpose, manipulative machine with several degrees of freedom, for use in industrial automation applications. It may be either fixed in place or mobile.

## 3.2 General Safety Instructions

Read the installation and operation instructions before using the equipment.

- Do not ride on the robot
- Do not exceed the maximum payload

  Payload decreases as slope increases. Refer to the user's guide
- Do not drop the robot, run it off a ledge, or otherwise operate it in an irresponsible manner
- Do not get the robot wet, or expose the equipment to rain or moisture
- Do not use power extension cords unless properly rated
- Do not continue to run the robot after hair, yarn, string, or any other items have become wound around the robot's axles or wheels
- Never access the interior of the robot with the charger attached

  Immediately disconnect the battery pack when removing the access cover.
- Do not use parts not authorized by Adept
- Do not use any charger not supplied by Adept
- Do not turn on the robot without the antennas in place
- Although the laser is Class 1 (eye-safe), Adept recommends you not look into it

## 3.3 Intended Use

The Adept equipment is not intended for use in any of the following situations:

- In hazardous (explosive) atmospheres
- In life-support systems
- In residential installations
- Where the Adept equipment will be subject to extremes of heat or humidity.
- In mobile, portable, marine, or aircraft systems

**NOTE**: The gyroscopic navigation used in Adept mobile robots requires a stationary environment for optimum accuracy. Therefore, Adept does not recommend them for use on a ship, train, aircraft, or other "moving" environment.

**CAUTION**: The instructions for operation, installation, and maintenance given in this guide and the robot user's guide must be strictly observed.

Non-intended use of Adept equipment can:

- Cause injury to personnel
- Damage the robot or other equipment
- Reduce system reliability and performance

Adept mobile robots are intended for use on level floors, in wheelchair-accessible areas.

The body of the robot must not come into contact with liquids. The drive wheels can tolerate damp floors, but the body of the robot must remain dry.

All persons that install, commission, operate, or maintain the robot must:

- Have the necessary qualifications
- Read and precisely follow the instructions in this safety guide
- Read and precisely follow the instructions in the robot user's guide

If there is any doubt concerning the application, ask Adept to determine if it is an intended use or not.

## 3.4 Qualification of Personnel

This guide assumes that all personnel have attended an Adept training course and have a working knowledge of the system. The user must provide the necessary additional training for all personnel who will be working with the system.

As noted in this guide, certain procedures should be performed only by skilled or instructed persons. For a description of the level of qualification, Adept uses the standard terms:

- **Skilled persons** have technical knowledge or sufficient experience to enable them to avoid the dangers, electrical and/or mechanical
- **Instructed persons** are adequately advised or supervised by skilled persons to enable them to avoid the dangers, electrical and/or mechanical

All personnel must observe industry-prescribed safety practices during the installation, operation, and testing of all electrically-powered equipment. To avoid injury or damage to equipment, always remove power by disconnecting the AC power from the source before attempting any repair or upgrade activity. Use appropriate lockout procedures to reduce the risk of power being restored by another person while you are working on the system.

**WARNING**: Before working with the robot, every entrusted person must confirm that they:

- Have received the guides (both this guide, and the robot user's guide)
- Have read the guides
- Understand the guides
- Will work in the manner specified by the guides

## 3.5 Safety Aspects While Performing Maintenance

**DANGER:** During maintenance of the charging station, disconnect the AC power cord to the charging station. Keep it locked up until you are done with maintenance.

**DANGER:** During maintenance and repair, disconnect the batteries of the robot as soon as possible. Avoid shorting the terminals of the batteries.

## 3.6 What to Do in an Emergency Situation

Press any E-Stop button (a red push-button on a yellow background/field) and then follow the internal procedures of your company or organization for an emergency situation. If a fire occurs, use $CO_2$ to extinguish the fire.

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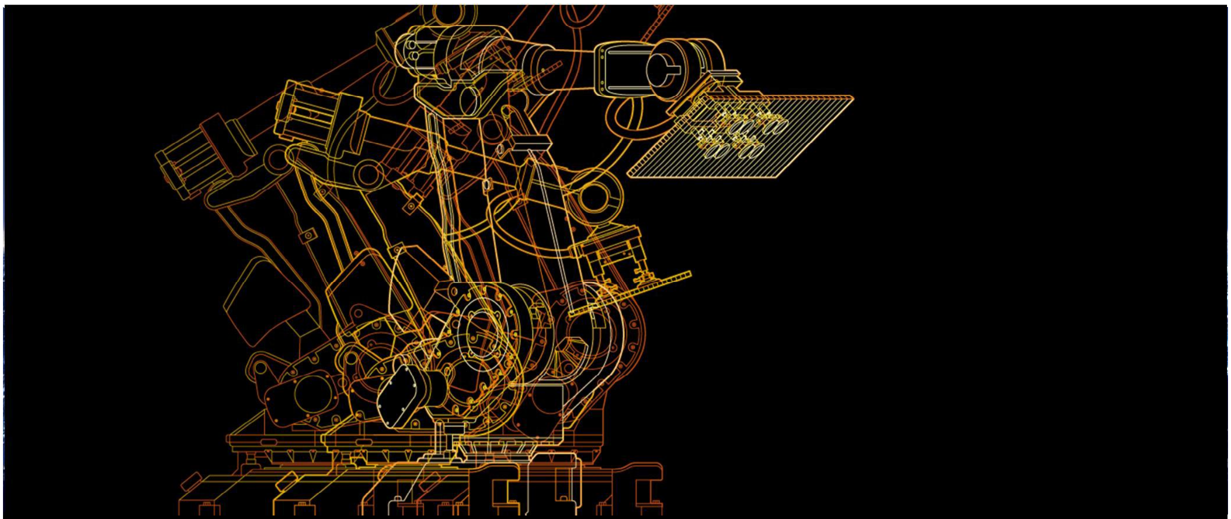


Björn Matthias, ABB Corporate Research, 2014-03-10

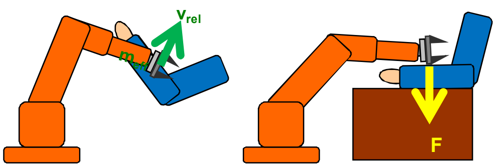
# Industrial Safety Requirements for Collaborative Robots and Applications

## ERF 2014 – Workshop: Workspace Safety in Industrial Robotics: trends, integration and standards

Power and productivity for a better world™ ABB

## Safety Requirements for Collaborative Robots and Applications


- Safety Standards for Applications of Industrial Robots
  - ISO 10218-1, ISO 10218-2
  - Related standards and directives
- Safety Functions of Industrial Robot Controller
  - Review of basic safety-related functions
  - Supervision functions
- Present Standardization Projects
  - ISO/TS 15066 – Safety of collaborative robots
  - Biomechanical criteria
- Collaborative operation




ABB

## Safety Standards for Applications of Industrial Robots
## ISO 10218-1, ISO 10218-2

### ISO 10218-1

- Robots and robotic devices — Safety requirements for industrial robots — Part 1: Robots
- Scope
  - Industrial use
  - Controller
  - Manipulator
- Main references
  - ISO 10218-2 – Robot systems and integration

Common references

ISO 13849-1 / IEC 62061 – Safety-related parts of control systems
IEC 60204-1 – Electrical equipment (stopping fnc.)
ISO 12100 – Risk assessment
ISO 13850 – E-stop

### ISO 10218-2

- Robots and robotic devices — Safety requirements for industrial robots — Part 2: Robot systems and integration
- Scope
  - Robot (see Part 1)
  - Tooling
  - Work pieces
  - Periphery
  - Safeguarding
- Main references
  - ISO 10218-1 – Robot
  - ISO 11161 – Integrated manufacturing systems
  - ISO 13854 – Minimum gaps to avoid crushing
  - ISO 13855 – Positioning of safeguards
  - ISO 13857 – Safety distances
  - ISO 14120 – Fixed and movable guards

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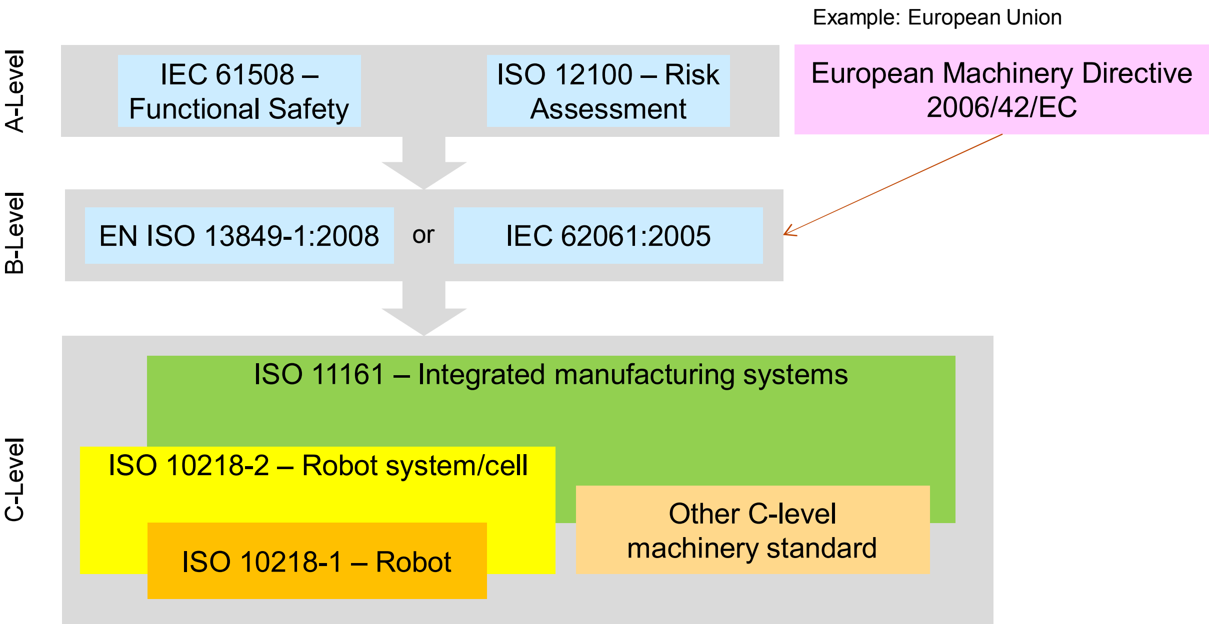
## Safety Standards for Applications of Industrial Robots
## Related Standards and Directives

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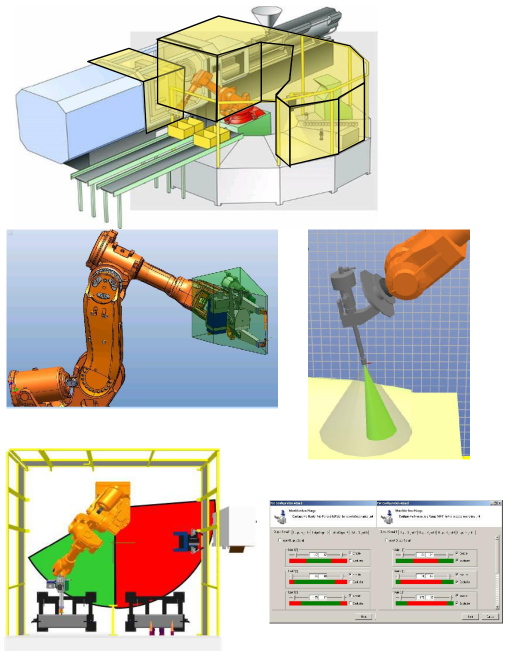
# Safety Functions of Industrial Robot Controller
## Review of Basic Safety-Related Functions

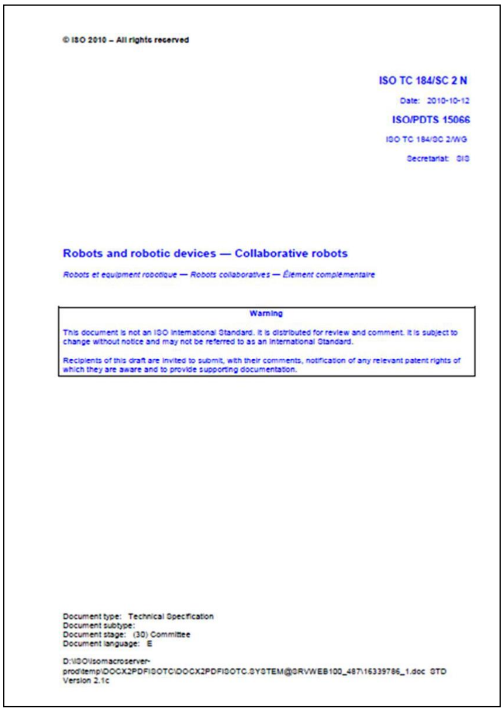

- E-stop
- Protective stop
  - Stop categories (cat. 0, cat. 1, cat. 2 as per IEC 60204-1)
- Operating modes
  - Automatic / manual / manual high-speed
- Pendant controls
  - Enabling
  - Start / restart
  - Hold-to-run
- Limit switches
- Muting functions
  - Enable / limits switches / …

# Safety Functions of Industrial Robot Controller
## Supervision Functions



- Basic supervision of robot motion, i.e. motion executed corresponds to motion commanded
- Supervision of kinematic quantities
  - Position
    - TCPs, elbow, solid model of manipulator, tool
  - Speed
    - TCPs, elbow, …
  - Acceleration, braking
- Possibility: Supervision of dynamic quantities, esp. for collaborative operation
  - Torques
  - Forces
- Possibility: Application-related / user-defined supervision functions

# Present Standardization Activities
# ISO/TS 15066 – Safety of Collaborative Robots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ISO TC 184/SC 2 N

Date: 2010-10-12

ISO/PDTS 15066

ISO TC 184/SC 2/WG

Secretariat: SIS

**Robots and robotic devices — Collaborative robots**

*Robots et equipment robotique — Robots collaboratives — Élément complémentaire*

**Warning**

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Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Document type: Technical Specification
Document subtype:
Document stage: (30) Committee
Document language: E

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Version 2.1c

- Design of collaborative work space
- Design of collaborative operation
  - Minimum separation distance $S$ / maximum robot speed $K_R$
  - Static (worst case) or dynamic (continuously computed) limit values
  - Safety-rated sensing capabilities
  - Ergonomics
- Methods of collaborative working
  - Safety-rated monitored stop
  - Hand-guiding
  - Speed and separation monitoring
  - Power and force limiting (biomechanical criteria!)
- Changing between
  - Collaborative / non-collaborative
  - Different methods of collaboration
- Operator controls for different methods, applications
  - Question is subject of debate: What if a robot is purely collaborative? Must it fulfill all of ISO 10218-1, i.e. also have mode selector, auto / manual mode, etc.?

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# Safety Requirements for Collaborative Robots and Applications

- Short Introduction to Human-Robot Collaboration (HRC)
  - Evolution of Safety Concepts
  - Definition of Collaborative Operation
  - Types of Collaborative Operation
  - Examples of Collaborative Operation
- Collaborative Application Scenarios
  - ABB Dual-Arm Concept Robot
  - Other Relevant Robot Developments
- Present Challenges for Collaborative Small-Parts Assembly (SPA)
  - Safety
  - Ergonomics
  - Productivity
  - Application Design
  - Ease-of-Use

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## Short Introduction to HRC
## Evolution of Safety Concepts

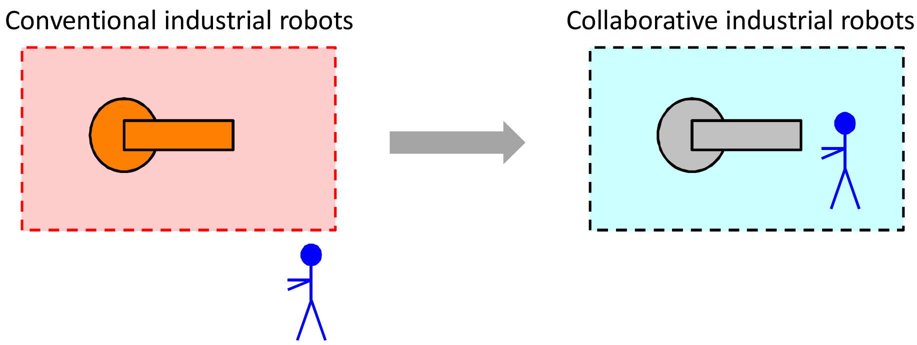
absolute separation of robot and human workspaces

complete union of robot and human workspaces

Discrete safety
→ No HRC

Safety controllers
→ Limited HRC

Harmless manipulators
→ Full HRC

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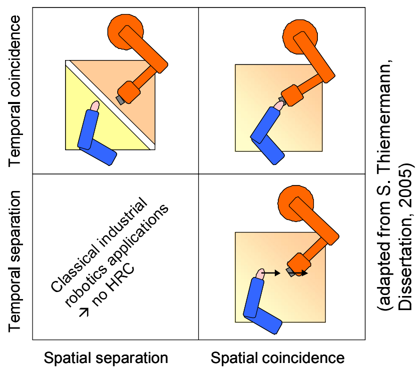
## Short Introduction to HRC
## Definition of Collaborative Operation





- ISO 10218-1:2011, clause 3.4
  - ***collaborative operation***
    *state in which purposely designed robots work in direct cooperation with a human within a defined workspace*
- Degree of collaboration
  1. Once for setting up (e.g. lead-through teaching)
  2. Recurring isolated steps (e.g. manual gripper tending)
  3. Regularly or continuously (e.g. manual guidance)

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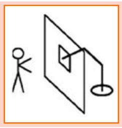
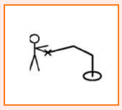
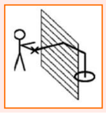
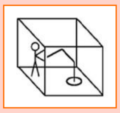
# Safety Functions of Industrial Robot Controller
## Types of Collaborative Operation According to ISO 10218-1

| ISO 10218-1, clause | Type of collaborative operation | Main means of risk reduction | Pictogram (ISO 10218-2) |
|---|---|---|---|
| 5.10.2 | Safety-rated monitored stop<br>(Example: manual loading-station) | No robot motion when operator is in collaborative work space |  |
| 5.10.3 | Hand guiding<br>(Example: operation as assist device) | Robot motion only through direct input of operator |   |
| 5.10.4 | Speed and separation monitoring<br>(Example: replenishing parts containers) | Robot motion only when separation distance above minimum separation distance |   |
| 5.10.5 | Power and force limiting by inherent design or control<br>(Example: *ABB Dual-Arm Concept Robot* collaborative assembly robot) | In contact events, robot can only impart limited static and dynamics forces | |

# Safety Functions of Industrial Robot Controller
## Types of Collaborative Operation According to ISO 10218-1

| | Speed | Separation distance | Torques | Operator controls | Main risk reduction |
|---|---|---|---|---|---|
| Safety-rated monitored stop | Zero while operator in CWS* | Small or zero | Gravity + load compensation only | None while operator in CWS* | No motion in presence of operator |
| Hand guiding | Safety-rated monitored speed (PL d) | Small or zero | As by direct operator input | E-stop; Enabling device; Motion input | Motion only by direct operator input |
| Speed and separation monitoring | Safety-rated monitored speed (PL d) | Safety-rated monitored distance (PL d) | As required to execute application and maintain min. separ. distance | None while operator in CWS* | Contact between robot and operator prevented |
| Power and force limiting | Max. determined by RA⁺ to limit impact forces | Small or zero | Max. determined by RA⁺ to limit static forces | As required for application | By design or control, robot cannot impart excessive force |

* CWS = Collaborative Work Space

⁺ RA = Risk Assessment

# Safety Functions of Industrial Robot Controller
# Collaborative Operation (1)

**Safety-rated monitored stop**
(ISO 10218-1, 5.10.2, ISO/TS 15066)

- Reduce risk by ensuring robot standstill whenever a worker is in collaborative workspace
- Achieved by
  - Supervised standstill - Category 2 stop (IEC 60204-1)
  - Category 0 stop in case of fault (IEC 60204-1)
- Application
  - Manual loading of end-effector with drives energized
  - Automatic resume of motion

---

**Hand guiding**
(ISO 10218-1, 5.10.3, ISO/TS 15066)

- Reduce risk by providing worker with direct control over robot motion at all times in collaborative workspace
- Achieved by (controls close to end-effector)
  - Emergency stop, enabling device
  - Safety-rated monitored speed
- Application
  - Ergonomic work places
  - Coordination of manual + partially automated steps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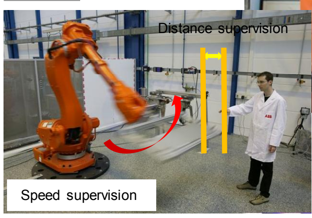
# Safety Functions of Industrial Robot Controller
# Collaborative Operation (2)

**Speed and separation monitoring**
(ISO 10218-1, 5.10.4, ISO/TS 15066)

- Reduce risk by maintaining sufficient distance between worker and robot in collaborative workspace
- Achieved by
  - distance supervision, speed supervision
  - protective stop if minimum separation distance or speed limit is violated
  - taking account of the braking distance in minimum separation distance
- Additional requirements on safety-rated periphery
  - for example, safety-rated camera systems

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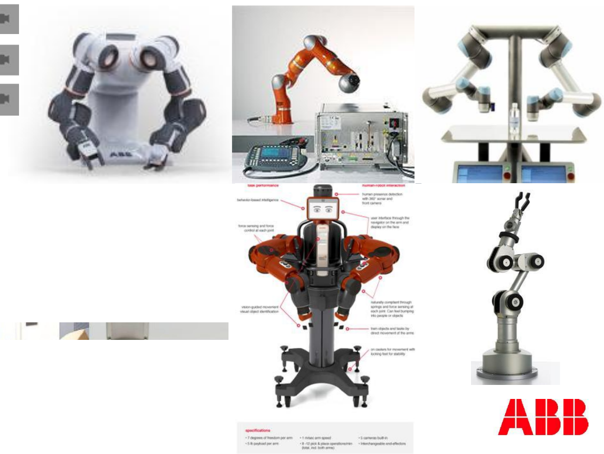
**Power and force limiting by inherent design or control**
(ISO 10218-1, 5.10.5, ISO/TS 15066)

- Reduce risk by limiting mechanical loading of human-body parts by moving parts of robot, end-effector or work piece
- Achieved by low inertia, suitable geometry a material, control functions, …
- Applications involving transient and/or quas physical contact (SPA = small parts assemb



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# Safety Functions of Industrial Robot Controller
## Collaborative Operation (3)

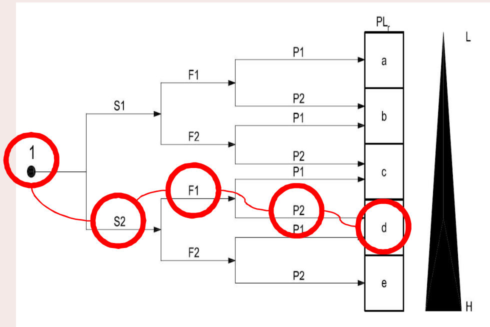
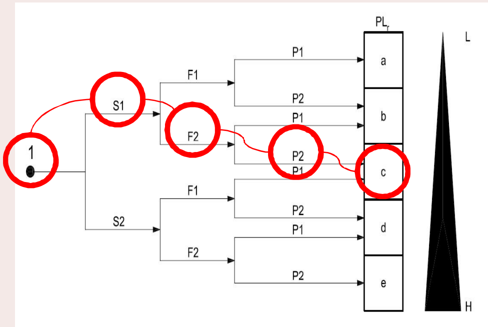
| **Standard industrial robot** | **Special robots for collaborative operation** (following ISO 10218-1, clause 5.10.5) |
| --- | --- |
| Injury severity S2 (irreversible) | Injury severity S1 (reversible) |
| Exposure F1 (rare) | Exposure F2 (frequent) |
| Avoidability P2 (low) | Avoidability P2 (low) |
|  |  |
| Required safety performance level: PL d | Required safety performance level: PL c |



ABB-activities in standardization:
ISO/TC 184/SC 2/WG 3 “Robots and robotic devices - Industrial safety”
DIN NA 060-30-02 AA “Roboter und Robotikgeräte”

Present projects in standardization:
ISO/TS 15066 “Collaborative robots – safety”
ISO/TS on manual loading stations
Upcoming 2014: review of ISO 10218-1, -2

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# Biomechanical Criteria

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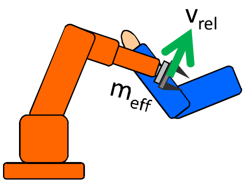
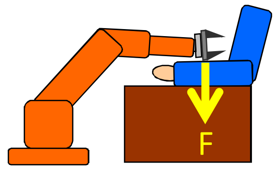
# Biomechanical Limit Criteria
## Types of Contact Events

| ISO / TS 15066 – clause 5.4.4 "Power and force limiting" | | | |
|---|---|---|---|
| Free impact / transient contact<br>• Contact event is "short" (< 50 ms)<br>• Human body part can recoil | | Constrained contact / quasi-static contact<br>• Contact duration is "extended"<br>• Human body part cannot recoil, is trapped | |
| Accessible parameters in design or control<br>• Effective mass (robot pose, payload)<br>• Speed (relative) | | Accessible parameters in design or control<br>• Force (joint torques, pose) | |
| Pain threshold | Minor injury threshold | Pain threshold | Minor injury threshold |
| Highest loading level accepted in design | Highest loading level accepted in risk assessment in case of single failure | Highest loading level accepted in design | Highest loading level accepted in risk assessment in case of single failure |

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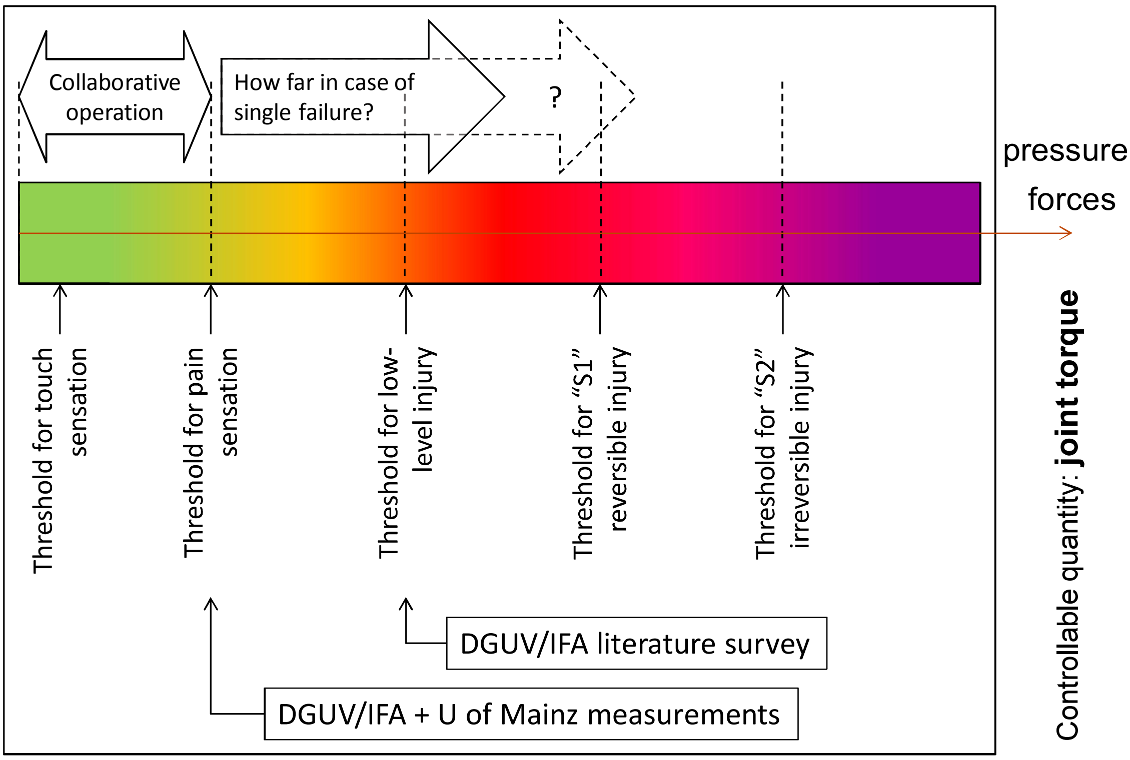
# Quasi-static contact – Severity measures

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# Biomechanical Limit Criteria
## Barrett Technologies

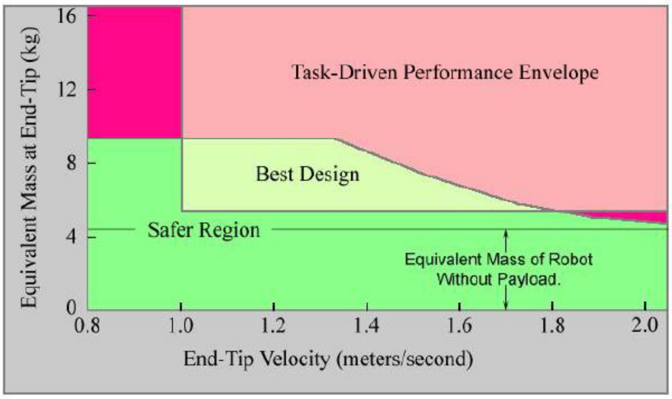


Figure 18 - Safety diagram for the robot design example.

Intrinsically Safer Robots, Prepared May 4, 1995, for the NASA Kennedy Space Center as the Final Report under NASA contract #NAS10-12178

http://www.smpp.northwestern.edu/savedLiterature/UlrichEtAlIntrinsicallySaferRobots.pdf

- Early work by W. Townsend et al. at Barrett Technologies
- Trade-off between moving mass and relative velocity

$$\frac{E}{A} = \frac{mv^2}{2A} \approx 2\frac{J}{cm^2}$$

assuming

$$m = 4\ kg$$
$$v = 1\frac{m}{s}$$
$$A = 1\ cm^2$$



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# Biomechanical Limit Criteria
## Standford Univ

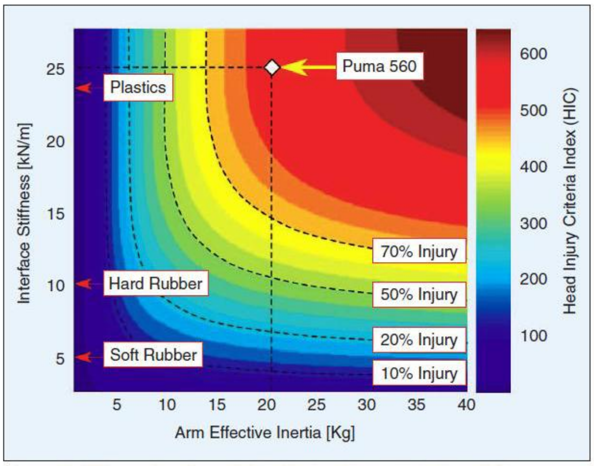


***Figure 1.*** *HIC as a function of effective inertia and interface stiffness.*

M. Zinn, O. Khatib, et al., IEEE Robotics & Automation Magazine, June 2004, p. 12-21

- Early work by Prof. Oussama Khatib et al.at Stanford University
- Transfer assessment criterion from automotive crashes
- Calculated curves
- Considers injury modes of brain collision with inside of skull, i.e. SDH (subdural hematoma), DAI (diffuse axonal injury), etc., but not superficial and less severe mechanisms

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2,5}(t_2 - t_1)$$



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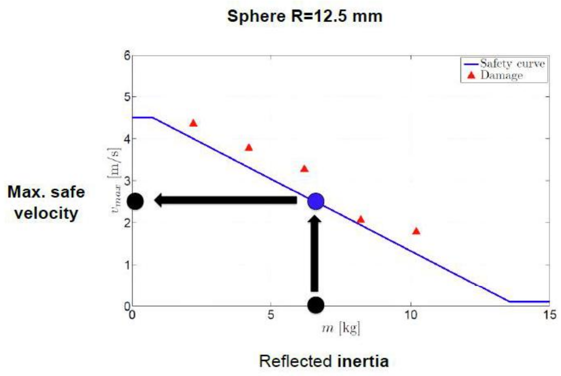
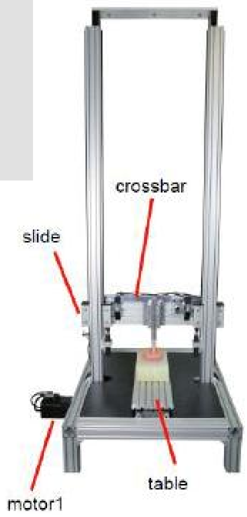
# Biomechanical Limit Criteria
## DLR




$$\frac{E}{A} = \frac{mv^2}{4\pi R^2} \approx 2\ \frac{J}{cm^2}$$




- DLR, Sami Haddadin et al.
- Drop test impact measurements on pig skin samples
- Microscopic analysis for evidence of onset of contusion
- Correlate to human soft tissue due to known similarity of properties
- "safety curves" determined for specific impactor shapes and range of relative velocity and reflected inertia

S. Haddadin, et al., IEEE Robotics & Automation Magazine, Dec. 2011, p. 20-34



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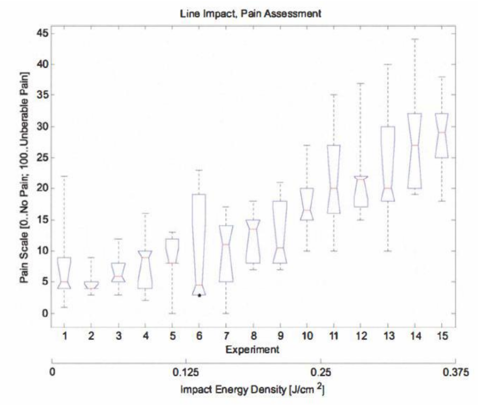
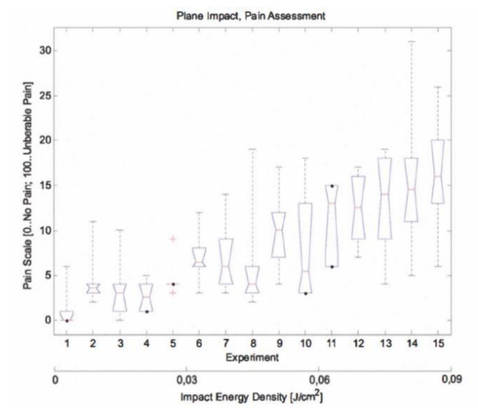
# Biomechanical Limit Criteria
## Univ of Ljubljana

| | | |
|---|---|---|
| - | 0 ... 20 | No pain |
| - | 20 ... 40 | Mild pain |
| - | 40 ... 60 | Moderate pain |
| - | 60 ... 80 | Horrible pain |
| - | 80 ... 100 | Unbearable pain |




- University of Ljubljana, B. Povse, M. Munich, et al.
- Transient impact with line and plane shaped impactors
- Pain rating on scale 0..100
- Onset of pain around 20
- → onset of pain around 0.1 to 0.2 J/cm$^2$

Povse et al., Proceedings of the 2010 3rd IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, The University of Tokyo, Tokyo, Japan, September 26-29, 2010



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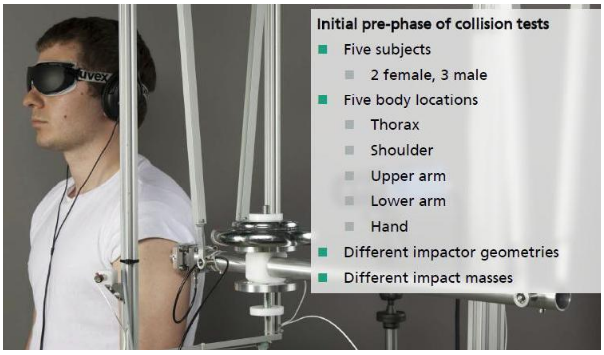
# Biomechanical Limit Criteria
# Fraunhofer IFF




R. Behrens, N. Elkmann et al., work in progress

- Fraunhofer IFF, Magdeburg, N. Elkmann et al.
- Collision tests with live test subjects
- Study has been ethically approved by the relevant commission
- Investigation of the onset of injury as defined by the following:
  - Swelling
  - Bruise
  - Pain
- Long-term goal:
  - Statistically significant compilation of verified onset of injury thresholds for all relevant body locations



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# Biomechanical Limit Criteria
# DGUV/IFA Limit Values

Table 2: Limit values for the forces, pressures and body deformation constant according to the body regions of the body model

| Body model – Main and individual regions with codification | | | Limit values of the required criteria | | | |
|---|---|---|---|---|---|---|
| BR | | Regions | CSF [N] | IMF [N] | PSP [N/cm²] | CC [N/mm] |
| 1. Head with neck | 1.1 | Skull/Forehead | 130 | 175 | 30 | 150 |
| | 1.2 | Face | 65 | 90 | 20 | 75 |
| | 1.3 | Neck (sides/neck) | 145 | 190 | 50 | 50 |
| | 1.4 | Neck (front/larynx) | 35 | 35 | 10 | 10 |
| 2. Trunk | 2.1 | Back/Shoulders | 210 | 250 | 70 | 35 |
| | 2.2 | Chest | 140 | 210 | 45 | 25 |
| | 2.3 | Belly | 110 | 160 | 35 | 10 |
| | 2.4 | Pelvis | 180 | 250 | 75 | 25 |
| | 2.5 | Buttocks | 210 | 250 | 80 | 15 |
| 3. Upper extremities | 3.1 | Upper arm/Elbow joint | 150 | 190 | 50 | 30 |
| | 3.2 | Lower arm/Hand joint | 160 | 220 | 50 | 40 |
| | 3.3 | Hand/Finger | 135 | 180 | 60 | 75 |
| 4. Lower extremities | 4.1 | Thigh/Knee | 220 | 250 | 80 | 50 |
| | 4.2 | Lower leg | 140 | 170 | 45 | 60 |
| | 4.3 | Feet/Toes/Joint | 125 | 160 | 45 | 75 |

| | | | |
|---|---|---|---|
| BR | Body region with codification | IMF | Impact force |
| Regions | Name of the individual body region | PSP | Pressure/Surface pressing |
| CSF | Clamping/Squeezing force | CC | Compression constant |

- BG/BGIA risk assessment recommendations according to machinery directive – Design of workplaces with collaborative robots, U 001/2009e October 2009 edition, revised February 2011
- Values for quasi-static and transient forces derived from literature study

http://publikationen.dguv.de/dguv/pdf/10002/bg_bgia_empf_u_001e.pdf



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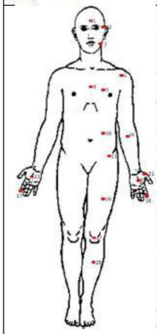
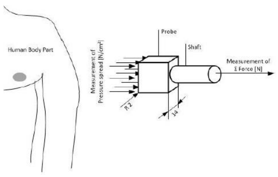
# Biomechanical Limit Criteria
## Univ Mainz – Preliminary Results

| Measurement localization | | | Force [N] | | | | Peak pressure [N/cm²] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Body model | | Description | N | Q1 | Median | Q3 | N | Q1 | Median | Q3 |
|  | 1 | Mid of forehead | 36 | 30 | 45 | 52 | 36 | 92 | 114 | 134 |
| | 2 | Temple | 36 | 17 | 24 | 27 | 35 | 50 | 85 | 154 |
| | 3 | Masticatory muscle | 35 | 13 | 18 | 21 | 32 | 46 | 100 | 197 |
| | 4 | Neck muscle | 35 | 15 | 18 | 25 | 33 | 51 | 108 | 153 |
| | 5 | 7th neck muscle | 36 | 27 | 39 | 48 | 36 | 103 | 149 | 194 |
| | 6 | Shoulder joint | 36 | 19 | 27 | 37 | 36 | 87 | 99 | 156 |
| | 7 | 5th lumbar vertebra | 36 | 50 | 64 | 72 | 36 | 109 | 133 | 190 |
| | 8 | Sternum | 36 | 31 | 42 | 53 | 36 | 82 | 99 | 118 |
| | 9 | Pectoral muscle | 25 | 25 | 30 | 46 | 25 | 63 | 89 | 161 |
| | 10 | Abdominal muscle | 35 | 21 | 29 | 38 | 34 | 73 | 119 | 247 |
| | 11 | Pelvic bone | 36 | 32 | 42 | 54 | 36 | 130 | 181 | 197 |
| | 12 | Deltoid muscle | 36 | 33 | 45 | 57 | 35 | 108 | 137 | 181 |
| | 13 | Humerus | 36 | 38 | 44 | 57 | 36 | 142 | 178 | 251 |
| | 14 | Radius bone | 36 | 32 | 38 | 50 | 36 | 116 | 158 | 193 |
| | 15 | Forearm muscle | 36 | 29 | 34 | 42 | 36 | 90 | 134 | 162 |
| | 16 | Arm nerve | 36 | 36 | 44 | 60 | 35 | 106 | 122 | 175 |
| | 17 | Forefinger pad nd | 36 | 51 | 63 | 83 | 36 | 117 | 163 | 230 |
| | 18 | Forefinger pad d | 36 | 50 | 61 | 80 | 36 | 124 | 159 | 215 |
| | 19 | Forefinger end joint nd | 36 | 38 | 47 | 67 | 36 | 160 | 208 | 269 |
| | 20 | Forefinger end joint d | 36 | 35 | 46 | 61 | 36 | 125 | 176 | 219 |
| | 21 | Thenar | 36 | 38 | 46 | 59 | 36 | 116 | 144 | 199 |
| | 22 | Back of the hand nd | 36 | 49 | 56 | 81 | 36 | 126 | 171 | 214 |
| | 23 | Back of the hand d | 36 | 45 | 58 | 72 | 35 | 145 | 183 | 215 |
| | 24 | Palm of the hand nd | 36 | 38 | 48 | 56 | 36 | 129 | 166 | 229 |
| | 25 | Palm of the hand d | 36 | 36 | 45 | 58 | 36 | 118 | 156 | 214 |
| | 26 | Thigh muscle | 36 | 44 | 57 | 72 | 36 | 95 | 133 | 236 |
| | 27 | Kneecap | 36 | 47 | 65 | 82 | 36 | 135 | 194 | 235 |
| | 28 | Shin splint | 36 | 39 | 55 | 67 | 36 | 131 | 168 | 236 |
| | 29 | Calf muscle | 36 | 49 | 63 | 79 | 35 | 107 | 128 | 196 |

- University of Mainz, Prof. A. Muttray
- Experimental research
- Ethics committee approved
- Ongoing to determine pain sensation thresholds for 30 different locations on body for quasi-static loading

A. Muttray et al.

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# Biomechanical Limit Criteria
## Additional Work

- Y. Yamada et al. – Univ. of Nagoya

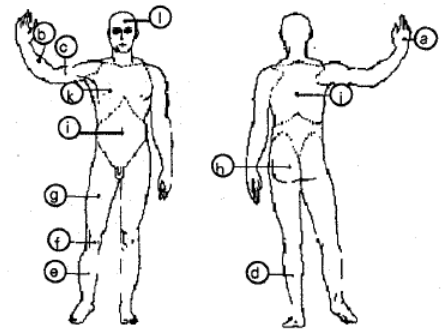


Fig.2 Measurement points for evaluating human pain tolerance

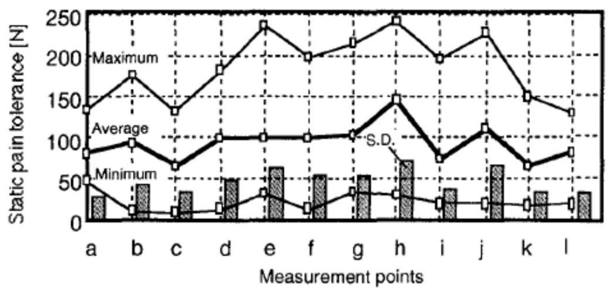


Fig.4 Experimental results of static pain tolerance

Probe diameter approx. 10 – 15 mm

Y. Yamada et al., IEEE/ASME TRANSACTIONS ON MECHATRONICS, VOL. 2, NO. 4, p. 230 (1997)

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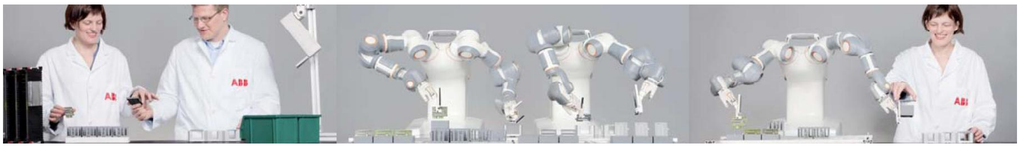
# Examples of Collaborative Robots for Power and Force Limiting

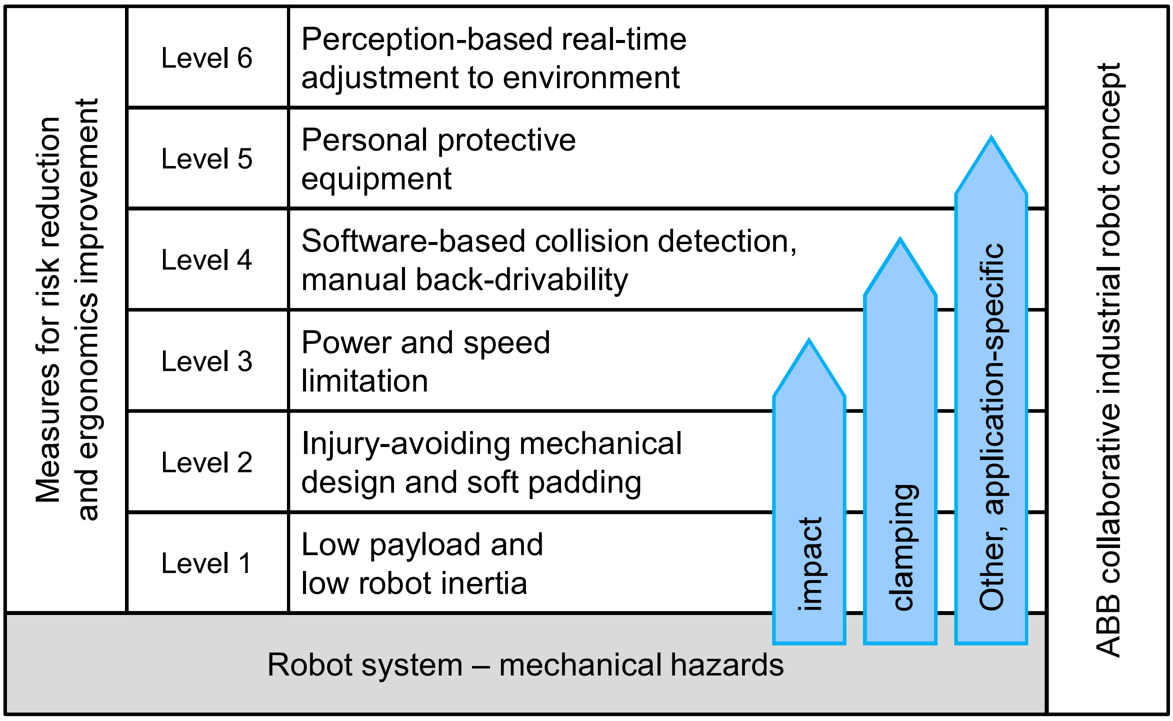
# → ABB Dual-Arm Concept Robot (DACR) a.k.a. “FRIDA”

## Collaborative Application Scenarios
## ABB Dual-Arm Concept Robot



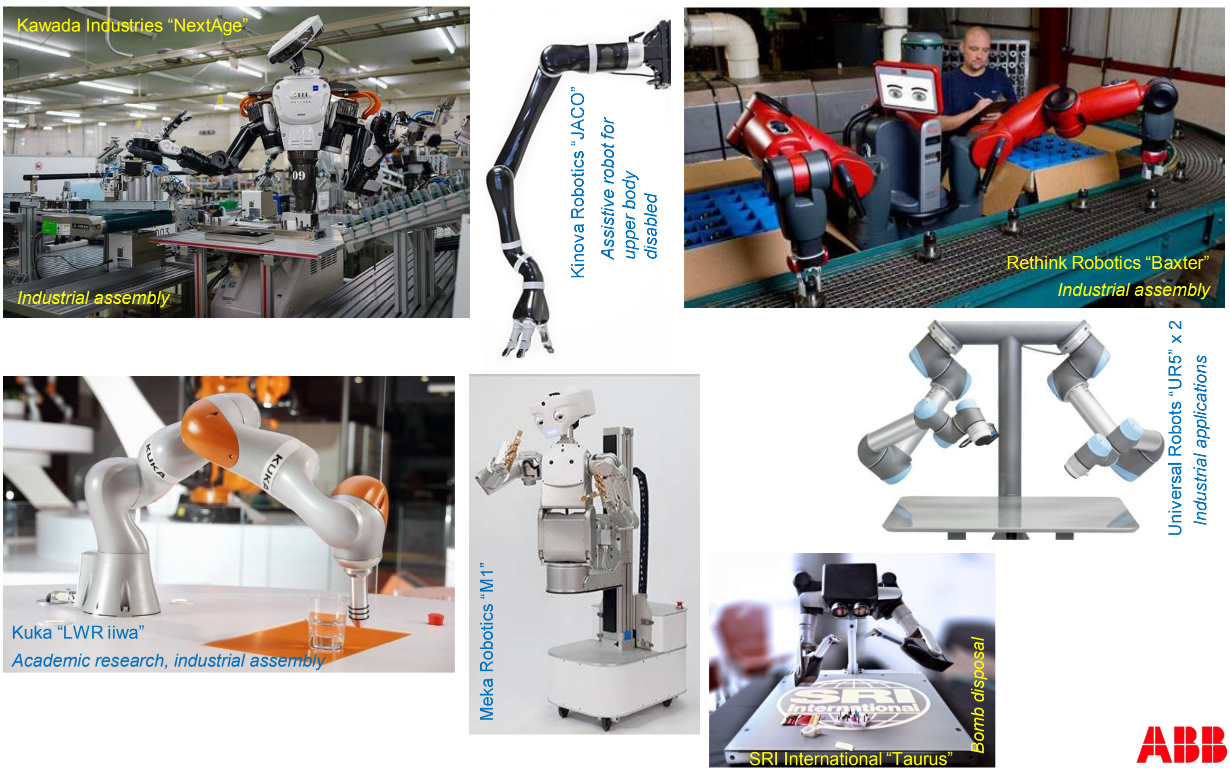
- Harmless robotic co-worker for industrial assembly
- Human-like arms and body with integrated IRC5 controller
- Agile motion based on industry-leading ABB robot technology
- Padded dual arms safely ensure productivity and flexibility
- Complements human labor for scalable automation
- Light-weight and easy to mount for fast deployment
- Multi-purpose lightweight gripper for flexible material handling

# Collaborative Application Scenarios
## Protection Levels






# Collaborative Application Scenarios
## Other Relevant Robot Developments



# Collaborative Application Scenarios
## Volkswagen Salzgitter – Glow Plug Assembly




# Collaborative Application Scenarios
## BMW Spartanburg – Door Sealing

# Ergonomics

# Productivity

# Application Design

# Ease-of-Use

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## Present Challenges for Collaborative SPA Ergonomics

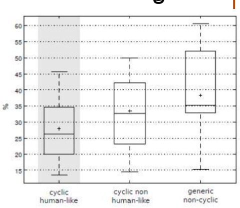
rosetta

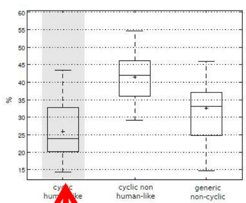
Worker acceptance of collaborative robots in production

- First experimental determination of stress indicators as function of motion characteristics

SCR – relative signal

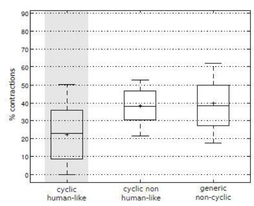
ECG – relative signal




Human-like elbow pattern

EMG – relative signal




Human-like motion


- All stress indicators show lowest levels for human-like motion
  - ECG – Electrocardiography
  - SCR – Skin conductivity, resistivity
  - EMG – Electromyography

Reference: P. Rocco, A. Zanchettin, DEI, Politecnico di Milano; work in EU-FP7 Project ROSETTA

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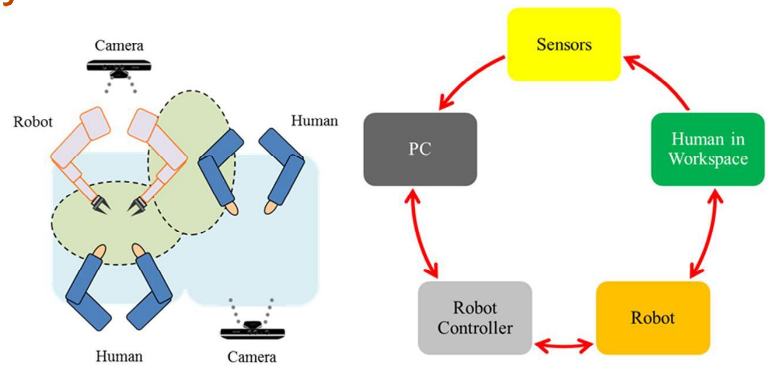
# Present Challenges for Collaborative SPA Productivity




(a) (b)

(c)

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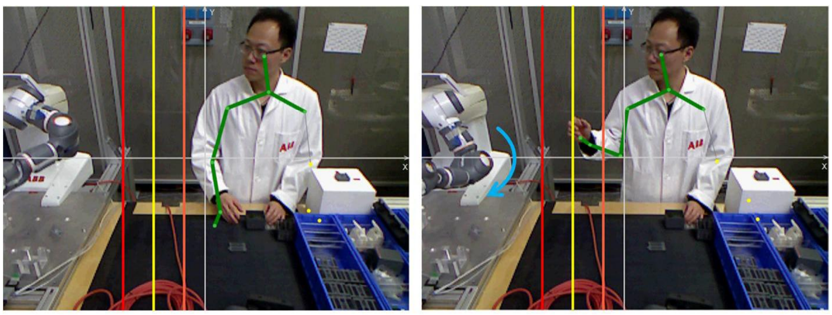
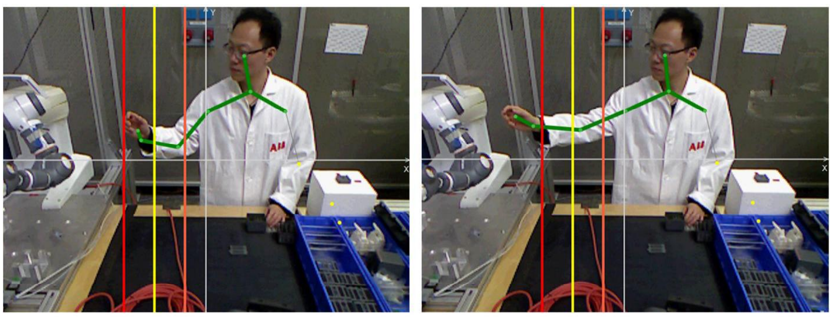
# Present Challenges for Collaborative SPA Productivity



Normal operation

Elbow down



Speed reduction

Standstill

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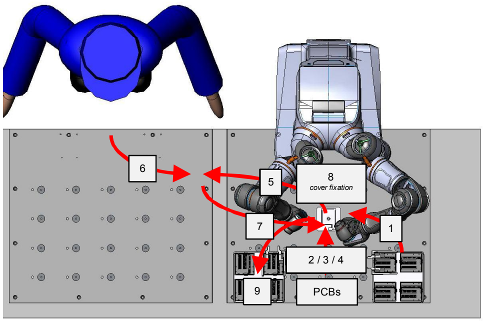
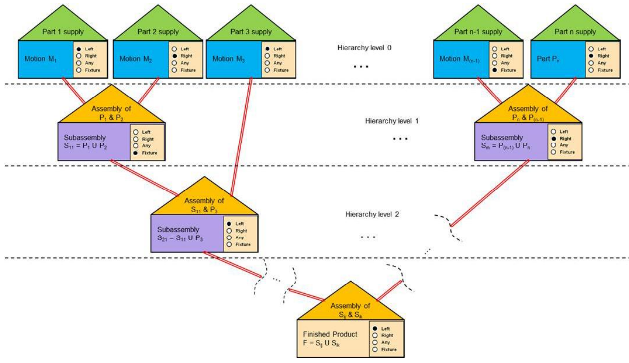
# Present Challenges for Collaborative SPA
## Application Design




| time slice | right arm (1) | left arm (2) | worker | housing no. left hand | PCB no. left hand | PCB no. right hand | housing+PCB subassembly no. | lid subassembly no. | complete assembly no. |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | | | | | |
| 2 | 0 | 2 | 0 | 1 | | | | | |
| 3 | 0 | 3 | 0 | | 1 | | | | |
| 4 | 5 | 4 | 0 | | 1 | 2 | | | |
| 5 | 6 | 7 | 0 | | 3 | 2 | | | |
| 6 | 0 | 8 | 11 | | 3 | | | 1 | |
| 7 | 9 | 0 | 11 | | | | 1 | 1 | |
| 8 | 10 | 0 | 11 | | | | 1 | 1 | |
| 9 | 0 | 0 | 12 | | | | | 1 | |
| 10 | 13 | 1 | 0 | 2 | | | | 1 | |
| 11 | 14 | 2 | 0 | 2 | | | | | 1 |
| 12 | 15 | 3 | 0 | | 4 | | | | 1 |
| 13 | 5 | 4 | 0 | | 4 | 5 | | | |
| 14 | 6 | 7 | 0 | | 6 | 5 | | | |
| 15 | 0 | 8 | 11 | | 6 | | | 2 | |
| 16 | 9 | 0 | 11 | | | | 2 | 2 | |
| 17 | 10 | 0 | 11 | | | | 2 | 2 | |
| 18 | 0 | 0 | 12 | | | | | 2 | |
| 19 | 13 | 1 | 0 | 3 | | | | 2 | |
| 20 | 14 | 2 | 0 | 3 | | | | | 2 |
| 21 | 15 | 3 | 0 | | 7 | | | | 2 |
| 22 | 5 | 4 | 0 | | 7 | 8 | | | |
| 23 | 6 | 7 | 0 | | 9 | 8 | | | |
| 24 | 0 | 8 | 11 | | 9 | | | 3 | |
| 25 | 9 | 0 | 11 | | | | 3 | 3 | |
| 26 | 10 | 0 | 11 | | | | 3 | 3 | |
| 27 | 0 | 0 | 12 | | | | | 3 | |
| 28 | 13 | 1 | 0 | 4 | | | | 3 | |
| 29 | 14 | 2 | 0 | 4 | | | | | 3 |
| 30 | 15 | 3 | 0 | | 10 | | | | 3 |
| 31 | 5 | 4 | 0 | | 10 | 11 | | | |
| 32 | 6 | 7 | 0 | | 12 | 11 | | | |
| 33 | 0 | 8 | 11 | | 12 | | | 4 | |
| 34 | 9 | 0 | 11 | | | | 4 | 4 | |
| 35 | 10 | 0 | 11 | | | | 4 | 4 | |
| 36 | 0 | 0 | 12 | | | | | 4 | |
| 37 | 13 | 0 | 0 | | | | | 4 | |
| 38 | 14 | 0 | 0 | | | | | | 4 |
| 39 | 15 | 0 | 0 | | | | | | 4 |

- Methodology is research topic
  - Annotated assembly graph
  - Assignment of assembly steps to robots, workers
  - Layout of work cell, assembly line
  - …

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# Present Challenges for Collaborative SPA
## Ease-of-Use


- Criteria and approaches are research topics
  - Alternatives to textual programming
  - Input modality must be intuitive and robust
  - Intelligent default values for configuration parameters
  - Selective hiding / exposing of complexity adapted to user group
  - …

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# Open Discussion
## What are your needs?

- Type of application
  - Assembly, pick-and-place, measurement & testing, …
  - Criteria for suitability of HRC
- Degree of automation
  - Distribution of tasks among robots / operators
  - Types of interfaces, handover, conveying, …
  - Frequency of changeover, typical lot sizes
- Keys for acceptance of partial automation / mixed human-robot environment
  - Ease-of-use
  - Application design
  - Ergonomics
  - Distribution of roles and responsibilities
  - …

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# Economic Motivations

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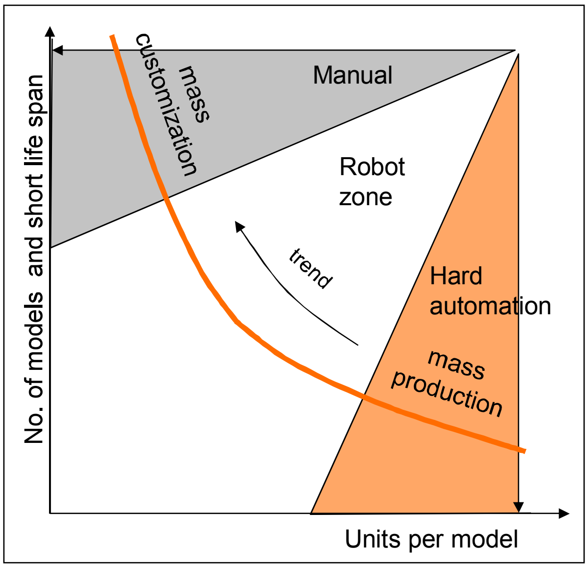
## Economic Background and Motivation




- Societal Trend
  - Individuality and differentiation with respect to peers
- Resulting Market Trend
  - Increasing no. of product variants
  - Decreasing product lifetime
  - Away from “mass production” towards “mass customization”
- Challenge to Industrial Production
  - Efficient handling of large range of variants and short model lifetimes
  - Common solution today: Mostly manual production in Asia

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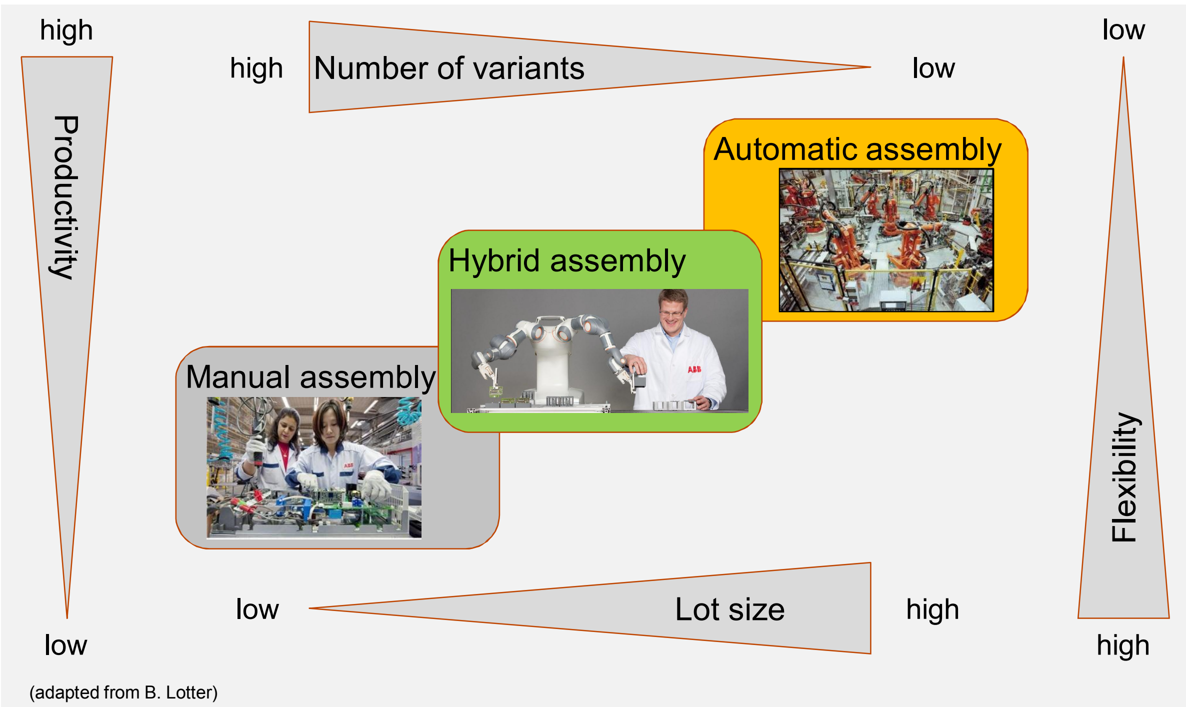
## Moving Humans + Robots Closer Together Productivity (1)

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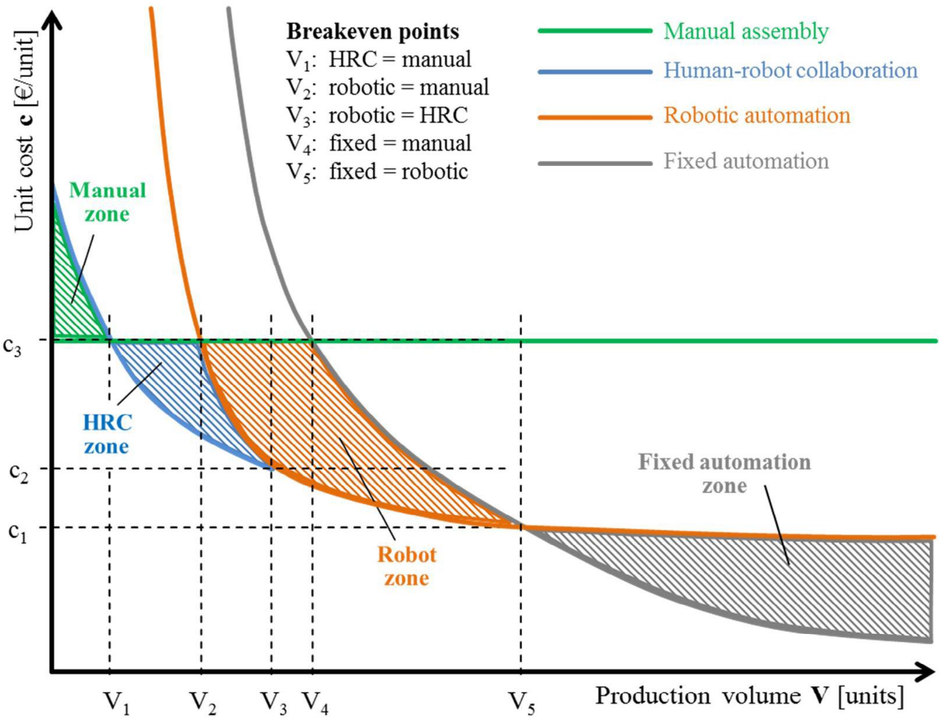
# Moving Humans + Robots Closer Together
## Productivity (2)

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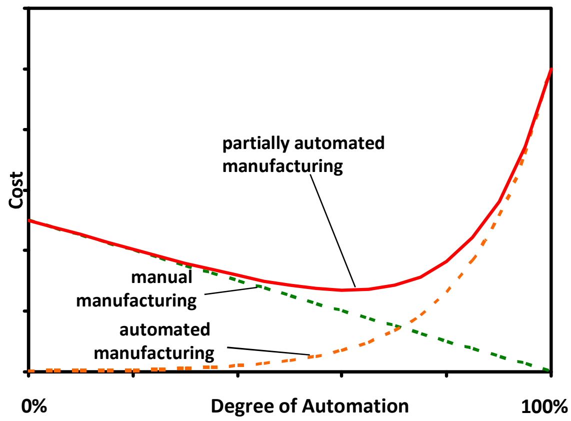
# Moving Humans + Robots Closer Together
## HRC for scalable degree of automation



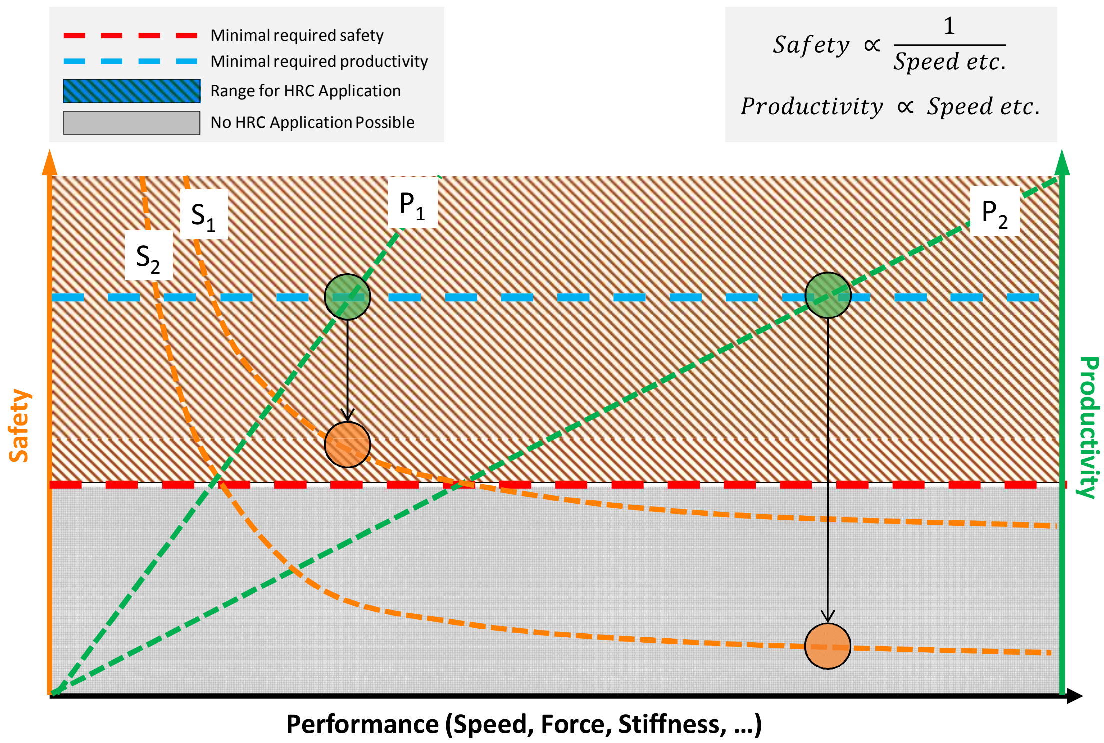

- Optimum degree of automation < 100%
  - Raising degree of automation becomes increasingly expensive, esp. on changeover
  - Manual manufacturing becomes increasingly competitive for remaining fraction of production task

- Worker Strengths
  - Cognition
  - Reaction
  - Adaptation
  - Improvisation
- Worker Limitations
  - Modest speed
  - Modest force
  - Weak repeatability
  - Inconsistent quality

- Robot Strengths
  - High speed
  - High force
  - Repeatability
  - Consistent quality
- Robot Limitations
  - No cognitive capability
  - No autonomous adaptation
  - Modest working envelope

- Synergy: HRC
  - Automation of applications requiring high flexibility (variants ↑, lot sizes ↓)
  - New ergonomics functionality
  - New applications in which robots previously have not been used

ABB




$S_k$ = example dependence of safety on speed for application no. k

$P_k$ = example dependence of productivity on speed for application no. k

Power and productivity
for a better world™

## Record for safety instructions

Rules for use of CENTAURO robot at/in … [enter place/site]

1. During the use of the Robot, I am obliged to follow all general safety regulations, in particular the regulations defined by … [enter place/site owner].

2. Only authorized persons may use the robot and only in presence of the robot operator: [enter name of operator]. This authorization can be obtained from the experiment supervisor [enter name of responsible person].

3. I understand that electrical equipment is considered without voltage only in the case that it is securely guarded against accidental activation. This is guaranteed only by unplugging the Robot power supply from the wall socket. If the Robot is switched off, but plugged in, it is considered to be with voltage (live).

4. It is the responsibility of the supervisor to ensure that the appropriate training in the use of the equipment has been given.

5. The operational space of the Robot is the area that is indicated by … [enter means of safeguard].

6. Any electrical or mechanical modifications to the robot or the robots operational space should be done by authorized personal and with the approval of the supervisor.

7. The operational space must be separated at all times by … [enter means of safeguard] and all persons should leave the operational space before connecting the Robot to voltage. Removing the … [enter means of safeguard] or entering the operational space is allowed only after unplugging the Robot power supply from the wall socket. The exceptions from this rule are described in §8 and §9.

8. If the task performed requires the presence of persons in the operational space of the robot, it is possible to enter the operational space only for the necessary time, and only after stopping the robot motion by pressing the Emergency Stop Button. The Emergency Stop Button can be released only after all persons left the operational space.

9. If the presence of the persons in the operational space of the robot is needed while the robot can move, it is possible only after ensuring all conditions bellow are satisfied:

a) The Robot is used in manual mode only.

b) The Robot is watched by two persons. It is required that one person is controlling the Robot, and at least one person is an employee of … [enter responsible organization].

c) The Robot velocity is set to the minimal speed satisfying conditions of the experiment, but not exceeding 20 % of the robot's maximal speed.

d) The maximal speed of the Robot's articulated parts is high, so the user must be aware of the danger this presents to persons in the operational space of the robot.

10. Do not leave loose papers lying around. General cleanliness/tidiness will help prevent accidents.
11. Never stand on chairs or desks when reaching for height. Always use a step stool or an appropriate stepladder.
12. Do not carry loads such that the weight may be dangerous or vision obscured.

13. Pay attention to appropriate clothing. Avoid wearing loose clothing, scarves, ties, open long hair, etc.

I hereby declare that I understand these rules and that I will comply with these rules.

Name, surname (legibly in capital letters): ............................................................

[enter place] : ....../......./....... Instructions given by: ………………………….

Signature Signature