Implementation of Collaborative Robot Applications

A Report from the Industrial Working Group

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# Implementation of Collaborative Robot Applications

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About the working group

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Summary

This document aims to provide guidelines to implement collaborative applications in compliance with relevant safety standards. Unlike regular applications where robots and operators are separated by fixed fences, collaborative applications enable overlap between robot and operator workspaces. According to ISO 10218-1, the 4 types of collaboration are identified as:

- Safety Monitored Stop: the operator works only when the robot is stationary
- Hand Guiding: the operator programs the robot trajectories by hand guiding
- Speed and Separation Monitoring: the robot’s speed varies according to the proximity of the operator
- Power and Force Limiting: the robot runs with limited power and force to ensure operators safety

Collaborative applications can also be classified according to the level of workspace sharing. Therefore 3 main categories are identified:

- Full Automation: the operator and the robot workspaces are separated by fences
- Cooperation: the workspace is shared, but tasks are performed with a stationary robot
- Collaboration: the workspace is shared, and tasks that are performed are not exclusive

This report relates particularly to truly collaborative applications, defined by the working group as "programmable electromechanical systems that have been designed, constructed, assessed and locked through a certified change control process, within a prescribed environment to operate within a tolerable level of risk in all reasonably foreseeable modes whilst collaborating in a shared workspace with a trained employee performing a standard operation." The recommendations given in this document to implement truly collaborative applications is a step-by-step approach which can be summarised as follows:

- Identify the objective to decide on the appropriate solution to adopt
- Design the application by considering the impacts of all its elements
- Select the robot with the right active, passive and third party safety measures
- Install the application by following the given standards
- Test and validate the application by using appropriate measuring tools
- Perform a risk assessment by following the appropriated standards and guidance

Collaborative applications can be implemented for varied industrial applications such as screwing, loading, handling, assembling, gluing and inspection. The group deem that it will ensure maximum value in ergonomics and quality improvement, line balancing, floor space optimisation and flexibility. However, their wide scale implementation is currently limited by the low payload, the low level of risk, and the limited speed, particularly in the automotive industry.
Introduction

Human-Robot collaboration has generated a considerable amount of interest in the robotics industry. Unlike traditional robot applications, collaborative applications allow operators to share their workspace safely. This benefits the manufacturing industry in terms of floor space utilisation, ergonomic improvement, productivity optimisation, and flexibility.

However, there is a perception from leading automotive manufacturers in Great Britain that their plants are falling behind their European and global competitors in the application of Collaborative Robots, causing manufacturing operations in Great Britain to be perceived as less productive. There are still some technical issues to overcome, but the issue is largely seen as the interpretation of standards and the development of implementation guidelines.

The “Cobot Working Group” is an initiative which aims to understand the root cause of this competitive disadvantage and to facilitate a safe, consistent and cost effective deployment of collaborative robot applications in automotive plants. It brings together the High Speed Sustainable Manufacturing Institute (HSSMI) and three automotive OEMs: Jaguar Land Rover, Nissan and Ford Motor Company, supported by the Health and Safety Executive (HSE). The Working Group commenced its activities with a set of objectives outlined from the Executive Committee in August 2016. The group met at regular intervals over a period of 10 months and followed a rigorous process that included workshops, consultations, interviews and gathering information through questionnaires. A wide variety of inputs were collected from Universities, robot manufacturers, Catapult centres, software providers, automotive OEM’s, trade organisations, and other European industrial safety organisations. The group was successful in:

- Providing a definition of a truly collaborative application and identify the differences to the standard collaboration modes;
- Understanding the legal requirements of safety compliance versus technical specifications;
- Developing implementation guidelines for truly collaborative applications along with guidance for risk assessment;
- Identifying key applications for automotive manufacturing;
- Establishing key limitations for collaborative applications;
- Developing research projects to identify future technology enablers;

To this end, this report aims to highlight some of the work of this group.
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Types and Levels of Human-Robot Collaboration

Types of Human-Robot Collaboration

According to ISO standard 10218-1 [1], 4 types of Human-Robot Collaboration are identified. These are illustrated in Figure 1.

• Safety Monitored Stop (Figure 1 (a)): In this case, the robot is mostly working on its own and stops when an operator enters its workspace. This collaboration feature can be implemented when a worker performs a precise operation on a workpiece while the robot is still handling it.

• Hand Guiding (Figure 1 (b)): The robot’s movements are controlled by the operator, who shows its trajectories by guiding it with his/her hands. This type of collaboration allows
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faster path teaching without programming the robot; it is particularly suitable for small production or tasks that are difficult to automate.

- Speed and Separation Monitoring (Figure 1 (c)): In this case, the robot adapts its speed relatively to the operator’s location in the workspace. Three safety zones (green, yellow, red) are defined, and the position of the operator is controlled by a vision system: the closer the operator is, the slower the robot works. When the operator is too close to the robot (i.e. in the red zone), the robot stops.

- Power and Force Limiting (Figure 1 (d)): Power and force limited robots are equipped with an embedded and programmable electromechanical system, which allows controlling forces and torques to operate within a tolerable level of risk in all reasonably foreseeable modes. These robots can work alongside humans without any additional safety device required.

Levels of Human-Robot Collaboration

Human-Robot Collaboration can also be classified according to the level of workspace sharing. As illustrated in Figure 2, five cases are identified [2]:

- Case 1: safety of the operator is ensured with physical fences. Sharing of workspace is not allowed in operation. Any contact is forbidden in this mode.
- Case 2: safety of the operator is ensured with sensor based safety systems. Sharing of workspace is forbidden in operation. The contact here is not allowed.
- Case 3: safety of the operator is ensured with a safety monitored stop. The workspace is shared, but the robot and the operator don’t perform their task simultaneously. A contact can then occur, but only when the robot is in stationary mode.
- Case 4: safety of the operator is ensured with speed and separation monitoring. The workspace is shared, but contacts between human and robots are not allowed. The robot’s speed is reduced when the operator comes closer to the robot. The robot is in stationary mode when the operator enters the red zone.
- Case 5: safety of the operator is ensured with an inbuilt power and force limiting feature in the robot. The workspace is shared in operation, and should there be a contact, no harm is caused by the operator.

With regards to Case 1 and 2, these can be implemented with traditional industrial robots with physical and sensor based safety systems. Case 3 and 4 fall in the cooperative workspace where contacts are possible only in stationary mode. Case 5 would constitute a collaborative workspace where contacts are possible with no harm.
Truly collaborative application definition

From the wider consultation process and the review of existing applications, members of the working group has successfully risk assessed and installed traditional industrial robot applications with physical and sensor based safety systems. In addition, cooperative workspace sharing with speed and separation monitoring and safety monitored stop have also been widely implemented in various applications in a safe manner. However, sharing of workspace and use of power and force limited features as a safety system is relatively novel and the group takes a systems approach to define a truly collaborative application. As illustrated in Figure 3, the collaborative application consists of: the robot (or any electromechanical system), the end effector, the production part, the environment and the trained operator.
We define a truly collaborative application as:

“A truly collaborative application is a programmable electromechanical system that has been designed, constructed, assessed and locked through a certified change control process, within a prescribed environment to operate within a tolerable level of risk in all reasonably foreseeable modes whilst collaborating in a shared workspace with a trained employee performing a standard operation.”

For truly collaborative applications, a risk assessment is extremely critical and should be performed for a safe application. Should there be a contact between the electromechanical system and the operator, the force and pressure should be acceptable according to the ISO/TS15066 biomechanical limits. The working group has developed guidelines for installation and risk assessment for truly collaborative applications.
Safety compliance and standards

There are legal duties on both the supplier of machinery for use at work and on the user of the machinery.

Supplier duties

Since 1995, all new machinery in scope of the Machinery Directive, which will include collaborative robots, has to be designed and constructed to meet common minimum European requirements for safety. The outward signs of compliance are CE marking on the equipment and a Declaration of Conformity or Incorporation, which is a document issued by the Responsible Person (normally the manufacturer) declaring the product conformity. To achieve compliance, the Responsible Person must undertake a conformity assessment process to meet the Directive’s obligations. This includes meeting all relevant Essential Health and Safety Requirements (EHSRs) for the product, producing comprehensive user instructions, and showing how compliance has been achieved in the technical file. These requirements have been implemented in GB by the Supply of Machinery (Safety) Regulations 2008 [3], as amended by the Supply of Machinery (Safety) (Amendment) Regulations 2011 [4]. The HSE website [5] has guidance on the law and responsibilities for both those supplying new machinery and those buying machinery. This guidance is applicable to the supply of collaborative robots and will be incorporated in collaborative applications.

User duties

Users of work equipment must ensure that the equipment is safe for its intended use. The HSE website has good guidance on how to ensure this [6]. The key legal duties are in the Provision and Use of Work Equipment Regulations 1998 (PUWER), which requires that equipment provided for use at work is:

- Suitable for the intended use
- Safe for use, maintained in a safe condition and inspected to ensure it is correctly installed and does not subsequently deteriorate
- Used only by people who have received adequate information, instruction and training
- Accompanied by suitable health and safety measures, such as protective devices and controls. These will normally include emergency stop devices, adequate means of isolation from sources of energy, clearly visible markings and warning devices
Regulation 11 of PUWER sets out the responsibilities of users to prevent access to dangerous parts:

- Regulation 11(1) requires employers to take effective measures to prevent access to dangerous parts of machinery or stop their movement before any part of a person enters a danger zone.
- Regulation 11(2) specifies the measures which you should take to prevent access to the dangerous parts of the machinery to achieve compliance with regulation 11(1).
- Regulation 11(3) sets out various requirements for guards and protection devices.
- Regulation 11(4) sets out requirements for protection appliances.

These requirements will apply to the whole of the cell, including the robot and end effector, regardless of which mode of human-robot collaboration is used. It is likely that complying with these duties will drive the type of collaboration that is appropriate. If the combination of a power and force limited robot with a specific type of end effector results in it being a ‘dangerous part’ then guarding, whether fixed or an electronic system, will be required.

The term ‘dangerous part’ has been established in health and safety law through judicial decisions. In practice, this means that if a piece of work equipment could cause injury, while being used in a foreseeable way, it can be considered as a dangerous part. A risk assessment, informed by this report, should be performed to determine if a specific installation contains a dangerous part and if so what protection system is appropriate. Full details about PUWER is contained in the Approved Code of Practice and guidance L22 [7].

**Use of standards**

The use of Standards in complying with European product safety Directives is not compulsory, but they can be useful when designing products. However, some European standards have a special legal status and define minimum acceptable levels for health and safety by supporting the essential requirements of these Directives, and if followed fully, may give a presumption of conformity to the relevant Directive's essential requirements. Standards may deal with broad general principles, aspects of safety common to many products, or be product specific. Below is a summary of these types and more information is contained on the HSE website [8]:

- A-level standards relate to fundamental principles for safety [8]. ISO 12100 specifies basic requirements to achieve safety in machine designing [9] and perform risk assessments on all types of machines. A-level standards also encompass the EU machinery directive 2006/42/EC which provides health and safety requirements and guidelines for products that are to be placed on the European market [10].
- B-level standards deal with common safety issues of all types of machines [11]. The machinery directive requires the integrator to provide a mandatory risk assessment
document that identifies any hazard which may arise from the collaborative application and safety measures to reduce the risk. It is a prerequisite for CE marking the system.

- C-level standards deal with a particular type of product [11]. ISO 10218-1 [1] specifies requirements and guidelines for use of industrial robots on their own in very general terms, and does not consider the robot as a complete machine. ISO 10218-2 [12] relates to industrial robots installed in a whole robot application. If these standards are applied, it can be assumed that the requirements of the EU Machinery Directive are followed. However, collaborative robots are not yet completed in ISO 10218-1 & 2, and these standards do not provide enough detailed specifications to ensure that all the safety requirements are satisfied. ISO/TS15066 [13] has been recently published to overcome the limitations of previous standards, it applies exclusively to collaborative robots and provides guidelines for implementing collaborative workspaces. This technical specification controls contacts between robots\(^1\) and humans by giving maximum permissible values of force and pressure on each body area when a collision occurs. However, ISO/TS15066 is not yet a standard. Statements may evolve in future editions and ISO standards dedicated to collaborative robots are expected to be published in the foreseeable future.

\[\text{Figure 4: Standards and directives for collaborative applications (adapted from [14])}\]

\(^1\) Including their end-effector.
Installation Guidelines of collaborative applications

The working group recommend to adopt the following approach to install a truly collaborative application in an industrial environment. As illustrated in Figure 5, a risk assessment should be performed at every stage of the installation process.

Identify the objective

Identifying the objective is the first step to analyse potential solutions. Selection of the automation solution along with the level of human robot collaboration will be done based on the application and the constraints involved. Following these points will allow selecting the appropriate automation solution to meet the requirements:

- Identify the application and the objective: what is the business need?
- Identify the industrial constraints related to the task, including cycle time, volume of production, flexibility, complexity of the task: what is the challenge to meet?
- Identify the solution: Is there any existing solution that should meet the needs?
- Identify which automation method is the more appropriate, considering the inherent risks with operators around: is full automation sufficient, or human-robot collaboration necessary?
- Identify the type of robot with appropriate safety features to implement, according to identified constraints and foreseeable risks.
Design the application

Once the automation solution and the need for human robot collaboration is established, an application design needs to be carried out. In the case of a collaborative application, a holistic approach that considers impacts on the whole application should be adopted to assess the application.

Assess what is the payload

Selection of the end effector and the work piece is critical to install a safe application. The inertia of the payload\(^2\) should be considered within a collaborative application, as heavy workpieces normally lead to exceeding force and pressure limits. Hazards related to the orientation, the shape, the sharpness and the temperature of workpieces should be minimised, considering the proximity of the operator.

Assess robot path along with payload interaction with operator and environment

Robot trajectories intended for collaborative operations are decisive. Normally, the robot travel ranges must be limited by means of the function (e. g. exclusion of sensitive body parts such as head and neck from the work area in the scope of the intended use). Contacts should be avoided in standard operations, and quasi static contacts or trap points should be avoided in most of the circumstances. Collaborative speed of an operation must be maintained whilst performing alongside an operator to satisfy the biomechanical forces and pressure limitations. For robot paths where contact with corresponding body regions are expected, the following foreseeable situations must be assumed:

- Manual intervention into the end effector area,
- Postures during process observation (e.g. leaning into or leaning over)
- Detection and intervention in the event of failures,
- Bumping of the robot arm against the body,
- Bumping of the end effector and the workpiece against the body.

Environmental hazards

Any other environmental hazards like smoke and harmful chemicals must be considered while designing the application.

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\(^2\) Including the workpiece and the end effector
Select the robot with the right safety measures

Besides the obligatory safety functions stated in EN ISO 10218-1, collaborative applications must demonstrate the selection of the right safety measures for a safe application, and that the requirements of PUWER have been met.

Active technical protective measures

- Safe monitoring / limitation of torque or force: considering the edge geometry of the robot surfaces which are involved in the work process, force or torque monitoring is required, which means that the pressure at contact surfaces is also monitored;
- Safe speed monitoring: by ensuring (e. g. for force and/or torque monitoring) that a stop reaction within the intended reaction time can take place. Normally, safe speed monitoring is necessary;
- Safe position monitoring: to define and limit work areas according to the load limits which are assigned to the body regions, a safely monitored position (range of movements) is normally required. Depending on the hazard exposure, a monitoring of individual axes must be provided in addition to the monitoring on the tool.

Passive protective measures

- Rounding of robot joints including the shape of the robot;
- Additional padding to soften impact;
- Suitable safeguards to avoid overlap for critical body regions.

Third party safety measures

- Mode selection and enabling switch: a lockable mode selection switch as well as an enabling switch are obligatory safety functions of industrial robots. For collaborative robot applications, according to ISO/TS 15066, an enabling switch may be dispensed with, if safety limits (e. g. speed, force, range of motion) ensure that all activities, such as servicing, maintenance, repair, setting and programming can be carried out as safely as using an enabling switch.
- Password protection and locking: the application should be password protected with a certified change control process to prevent unauthorised program changes. A locking system fixed with screws should be installed to prevent any unauthorised hardware adjustment.
- Cyber security protection: suitable cyber security protocols should be established for systems connected to servers to avoid any malfunction or misuse
Install the application

For truly collaborative applications, the working group recommends to follow the standards described on Table 1.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Section</th>
<th>Description</th>
</tr>
</thead>
</table>
| ISO 12100
“Safety of machinery, General principles for design, Risk assessment and risk reduction” | Table B1, 2 & 3 | These tables give a non-exhaustive list of hazards, hazardous situations and hazardous events to consider to perform risk assessment:
- Table B.1 gives examples of hazards
- Table B.2 gives a description of origins and consequences of typical hazards (i.e.: cutting parts, moving elements, electrical parts, operator posture...)
- Table B.3 gives examples of hazardous situations |
| ISO 10218-2
“Robots and robotic devices, safety requirements for industrial robots, Part 2: Robot systems and integration” | Section 5.11.2 (a) | General requirements of collaborative robot operation; points to consider to perform risk assessment: Robot characteristics, end-effector hazards, layout of the robot system, operator location, operator path, fixture design, design of robot guiding device, application-specific hazards, limitations caused by using PPE³, environmental specifications, performance criteria of safety functions |
| ISO 10218-2
“Robots and robotic devices, safety requirements for industrial robots, Part 2: Robot systems and integration” | Section 5.11.5.5 | Safety features to select for ensuring a safe working environment when using a truly collaborative robot |

³ Personal Protective Equipment
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ISO/TS 15066
“Robots and robotic devices, Collaborative robots”

<table>
<thead>
<tr>
<th>ISO/TS 15066</th>
<th>Section 4.2 (b)</th>
<th>Access and clearance factors to consider to reduce risks and hazards when designing a collaborative application.</th>
</tr>
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</table>

ISO/TS 15066
“Robots and robotic devices, Collaborative robots”

<table>
<thead>
<tr>
<th>ISO/TS 15066</th>
<th>Section 4.3.2 (b)</th>
<th>Identification of hazards related to robot applications, including:</th>
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<tbody>
<tr>
<td></td>
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<td>- end effector and workpiece hazards: lack of ergonomic design, sharp edges, loss of workpiece, protrusions; working with tool changer etc.;</td>
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<td></td>
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<td>- operation motion and location;</td>
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<td>- type of contact identification (transient or quasi-static), and exposed operator’s body regions;</td>
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<td>- design of the robot guiding device;</td>
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<td>- influence of the surroundings.</td>
</tr>
</tbody>
</table>

ISO/TS 15066
“Robots and robotic devices, Collaborative robots”

<table>
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<tr>
<th>ISO/TS 15066</th>
<th>Section 4.3.3</th>
<th>Identification and documentation of reasonably foreseeable tasks and hazards combination associated with the robot cell</th>
</tr>
</thead>
</table>

Table 1: ISO standards for collaborative applications

Test and validate the application

For truly collaborative applications where contact is intended in reasonable circumstances, a physical test for pressure and force is essential. The physical testing will document the severity of the impact and provide evidence for the risk assessment. Collision forces and pressures need to be measured to verify whether the limitations given by the standards are respected.

Several systems can be used to measure collision forces. For example, the GTE KMG 500 [15] is a portable dynamic force measurement device that analyses impulse and collision forces of collaborative robots, it can be used in combination with the Fuji pre-scale [16], which measures pressure distribution by using pressure-sensitive films that show red patches when pressure is applied. The colour density changes according to the level of pressure.
Risk assessment

Risk assessments for collaborative robot systems do not generally differ from procedures for other machines and robot systems. However, they should consider the immediate proximity of the operator to the robot system and derive appropriate protective measures. In 2009, the German Institute for Occupational Safety and Health of the Social Accident Insurance published guidelines that supplemented the requirements of ISO 12018:1&2 and the machinery directive [18] to design collaborative workspaces and assess collision risks. The following general guidelines were recommended by the working group:

- In workplaces that use collaborative robots, the probability of a collision between an operator and a collaborative robot must be minimised with suitable measures;
- The possibility of impact above neck region must be minimised;
- In case of a possible collision, only extensive touching areas may occur. Usually, point contacts should be avoided. For this purpose, suitable housings, covers or separating planes can be used;
- If there is a possible collision between a human being and a collaborative robot, no sharp, pointed, shearing or cutting edges and construction parts or rough surfaces may be present in the collision area;
- In accordance with the application and the risk assessment, speed for human robot collaboration should comply with the pressure and force limitations;
- Quasi Static contacts and trap points between the robot and the operator should be avoided in most circumstances

Specific risk assessment methods are company dependant. Further guidelines on risk assessment methods can be found in [14] and [19].
**Key applications**

Collaborative applications can be implemented in different industrial contexts. The group does not see these applications as a replacement for operators, but more from a standpoint of support to solve operational issues. These applications will have maximum value for the following situations:

- Ergonomic and occupational health improvements, by relieving operators from performing tough, painful, and repetitive tasks;
- Use as a third hand for the operator to ensure efficient and ergonomic operations;
- Line balancing activities to achieve a whole number of operators on the line;
- Quality improvement for tasks that require high precision;
- Better floor space utilisation;
- Versatile and flexible operations.

The working group identifies some key tasks that can be done in a collaborative mode; some of the typical applications implemented in the automotive industry are listed in the graphic below. However, there would be various other tasks that could be done via a collaborative application.

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**Figure 7: Key industrial applications (from [2])**

- **Screwing**
- **Loading**
- **Handling**
- **Assembly**
- **Gluing**
- **Inspection**
Limitations of collaborative robotics

Despite the significant emergence of collaborative robots in the industry, their wide scale implementation in an industrial environment remains challenging, particularly within the automotive industry with regards to the multiple constraints like cycle time, volume of production, flexibility and complexity of the task. Hence the range of collaborative applications are restricted due to the following:

- **Low payload:** in most cases, the payload does not exceed 15kg, which limits the type of workpieces to handle;
- **Low speed:** in collaboration mode, truly collaborative robots do not run at their highest speed considering the speed limitations given by the standards, which can cause difficulty to meet short cycle times;
- **Level of risk:** to ensure operators safety, collaborative applications will present risks which could be mitigated. However, the uncertainty of human behaviour needs to be taken into account which increases the level of perceived risk.
- **Limited applications:** shared workspaces for the robot and operator solve very specific problems within the automotive industry, other automation solutions have been deployed in a cost-effective manner.
Future technology enablers

Currently, collaborative applications are in the early stages of implementation on the shop floor. Members of the working group have had significant experience on implementing these systems safely on the shop floor. During the consultation process, the working group identified a significant need to risk assess applications in a virtual environment before installation. This would give the wider industry the confidence on selecting the right applications to enable safe human-robot collaboration.

A virtual tool to perform risk assessment on a collaborative operation is currently under development, as part of a research program named RACE (Risk Assessment for Collaborative work Environment). From inputs such as robot’s program, operator’s task, and CAD models of production parts and the environment, a simulation is performed to identify any risk of collision between the robot and the operator. This tool will then allow performing quicker risk assessments according to safety regulations, and to reduce the risk of collisions during a collaborative operation.

Figure 8: Overview of the RACE tool
Acknowledgments

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References


