POWER AND FORCE LIMITING TECHNIQUE AT COLLABORATIVE WORKPLACE

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Nowadays, the automotive industry still incorporates collaborative robots and their applications into the less traditional processes to automate them. The purpose is to make up for the skill gap, retain skilled staff, attract the younger generation, and increase quality. The paper brings a short overview of the automated collaborative workplace, including the PFL technique description and possibilities. Also, human-robot collaboration (HRC) is elaborated together with the example of such an automated workplace (with dual-arm robotic system participation). The specific contact (transient, quasi-static) between the human body and robotic system is described to fulfill the HRC and PFL technique. It also summarizes and explains ISO / TS 15066 details to apply this technique at automated assembly process example.

KEYWORDS

PFL Technique, Collaborative Robots, ISO / TS 15066, Transient Contact, Quasi-Static Contact

1 INTRODUCTION

The need for production flexibility has resulted in accepting cooperative automated workplaces as a viable alternative in the industry. Reasons come from the enhancing of the adaptability and requirements of customers to the contextually rich industrial environment. The idea of human-robot collaboration is, according to [Belingardi 2017] to fill the gap between manual and fully automated processes. Cooperative tasks (such as the assembly process) often generate different possible execution workflows. Therefore, various task assignments among operators and the robotic system can also be changing during operation. [Johannsmeier 2017] distributes assembly sub-tasks between a human and a collaborative robot to minimize workload or energy consumption per subtask. Proximity and common task between operator and robotic system have a substantial impact on the operator's safety.

Most importantly, we cannot realize a dynamic shared environment only by static safety analysis. As [Vysocky 2016] said, more advanced collaborative systems can provide compliance control-adjusting the movement by pushing it off. The most sophisticated is the entire elimination of collision by adjusting the trajectory of the whole movement [Durovsky 2014].

In any cooperative task that involves robotic systems, sharing workspace with the operator (such as assembly workplace), and the robot has to meet the dynamic challenges during application running. The robotic system in such an application requires awareness and information about the environment and emotional situations that can be occurred in its workspace [Velisek 2017]. In addition, within the automation of technological processes (such as assembly) and miniaturization, each technical piece of equipment (as a robotic system) is considered one of the main issues in solving signal and energy transmission, also [Hartansky 2020].

This field of research is commonly known as human-robot collaboration ("HRC"). A vast field tries to answer questions from an engineering perspective and a societal stance [Marvel 2020]. Discussion about "HRC" assumes that there must be the same level of interaction between the operator and the robotic system. It implies some level of collaborative functionality between the operator and the robotic system. There are four degrees of human-robot collaboration ("HRC"):

A. *Separate*: The operator and robotic system tasks are kept apart. They do not share workspaces, tools, or workpieces.

B. *Sequential*: The operator and robotic system tasks we can consecutively complete. The workspaces, tools, and workpieces may be shared, but there is a strict serialization of the tasks such that any sharing is temporally separated.

C. *Simultaneous*: The operator and robotic system tasks are executed concurrently and may involve working on different parts of the same workpiece but are focused on achieving the individual task goals.

D. *Supportive*: The operator and the robotic system work together simultaneously and with the same workpiece to complete a common task.

Sharing workspace is a relatively novel approach that needs a systematic approach for defining the collaborative application [Vagas 2016]. This application consists of the robotic system, end effector, assembled object, workplace, and trained operator (Figure 1). The "separate" principle of human-robot collaboration (HRC) is applied in laboratory conditions. Functional safety assessment according to the EN 6158 is needed to regularly deployment into the SMEs with natural conditions.

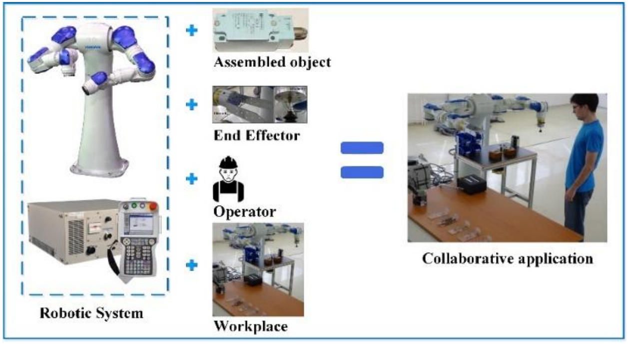

Figure 1. Collaborative application

For truly collaborative applications, a risk assessment is highly critical, and it is necessary to perform it for a safe application. Should there be contact between the robotic system and operator, the force and pressure should be acceptable according to the ISO / TS 15066 biomechanical limits. Despite the numerous deployment of collaborative robotic systems into the automotive industry, their implementation remains challenging regarding the constraints like cycle time or production volume [Mikolajek 2015]. The range of collaborative applications are as the following:

A. *Low payload* - does not exceed 15kg (in most cases), limiting the type of workpieces to handle.

B. *Low speed* - truly collaborative robotic systems do not run at their highest speed considering the speed limitations given by the standards, which can cause difficulty to meet short cycle times.

C. *Level of risk* - to ensure operators' safety, collaborative applications will present dangers that we need to mitigate. However, the uncertainty of operator behavior needs to be into account, which increases the level of perceived risk.

D. *Limited applications* - shared workspaces for the robotic system and operator, solve particular problems within the automotive industry. Other automation solutions we cannot consider as cost-effectively.

2 POWER AND FORCE LIMITING (PFL) ROBOTS

Automated activities at this concept are focused on using a new type of robotic system - a collaborative, which is for cooperation next to the operator. The principle consists of a specific operation, usually does not require safety features such as barriers or other optical. This robotic arm has advanced sensor systems, so the robotic system "senses" the over-acting forces during its operation. It is programmed to stop when it records an overload in power, increased pressure, or energy. These robotic systems manufacturers design to dissipate excess to the broadest possible area thanks to the rubber parts at the surface of the robotic arm. Many of these robotic systems are third-party certified so that they can work safely alongside humans (Figure 2).

Figure 2. Power and force limiting technique (PFL)

Research of this technique resulted in the already mentioned technical specification ISO / TS 15066, which complements the standard ISO 10218. This specification (in a very simplified form) determines what force (or rather mechanical pressure) and impact speed of robotic arm will cause even more painful pain at different parts of the human body, under other conditions - for example, in an open space impact (transient contact) or when pressed against a fixed obstacle (quasi-static contact). Medical/biomechanical requirements investigate how to measure the risk, and the potential danger for the operator when impacting the robotic system should be possible Table 1.

Body model – and individual regions with the codification			**Limit values of the injury severity criteria (CSF, IMF, PSP) and arranging factor for CC**			
Main body region	**Individual body regions**		**CSF [N]**	**IMF [N]**	**PSP [N/cm^2]**	**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)	145	190	50	50
	1.4	Neck (lateral)	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 / Hand 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
SF - Clamping / Squeezing force; **IMF** - Impact force; **PSP** - Pressure / Surface pressing; **CC** - Compression constant						

Table 1. Medical/Biomechanical requirements [ISO / TS 15066 2016]

For PFL robotic systems, physical contacts with a moving robotic arm are allowed. Still, the forces/pressures/energy absorbed during a collision need to be within human body part specific limits. It translates onto the lightweight structure, soft padding, no pinch points, and possible introduction of elastic elements on the robotic system side, combined with collision detection and response relying on motor load measurements, force/torque, or joint torque sensing. It addresses the interaction control methods for this post-impact phase. The performance of robotic systems complying with this safety requirement in terms of payload, speed, and repeatability is limited. The measurement of these values is contingent on the type of impact occurring between the robotic system and the operator. Results are classified as either transient or quasi-static, depending on the conditions of the effect. Suppose the operator is moving in the same direction as the robotic system. In that case, the impact won't be as strong as if the robotic system is running straight into the operator while he is standing still or moving towards it [Juhas 2012].

3 TRANSIENT CONTACT

This type of impact is referred to as „dynamic impact“ and describes a situation where the moving robotic system hits an operator's body part with the possibility to retract or recoil without clamping or trapping between the robotic system and the operator body part. This type of impact is of short duration (< 50 ms). It is on the assumption of the worst-case scenario, a complete inelastic contact situation.

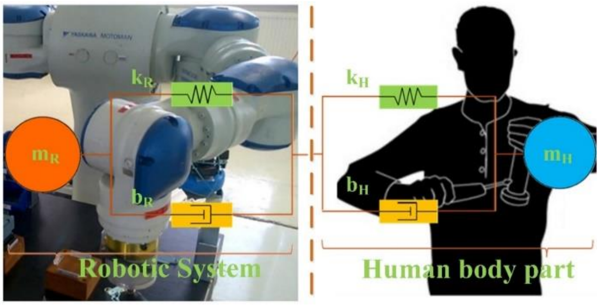

Figure 3. Transient contact between operator body and robotic system

Transient contact between operator body and robotic system (Figure 3) is characterized as "dumper-spring" system, where m_R is the effective moving mass of the robotic system at the point of contact *(expression of inertia)*; m_H is the effective weight at the end of contact of the operator's body part; k_R is the flexible component of the robotic system; k_H is the elastic component of the operator's body part; b_R is the damping component of the robotic system; b_H is the damping component of a part of the human body.

4 QUASI-STATIC CONTACT

This type of impact includes clamping of crushing situations. A part of the operator's body could be trapped between a moving part of the robotic system and a fixed or moving part of the automated workplace. In this precise situation, the robotic system will apply force/pressure on the trapped operator's body for an extended time until robotic arm removal. This type of contract requires a smaller force to reach the pain threshold. Pressures and forces applied during the contact quantify the hazard, which depends on the size of the contact area and the kinematics configuration of the robotic system and operator body at the time of the contact.

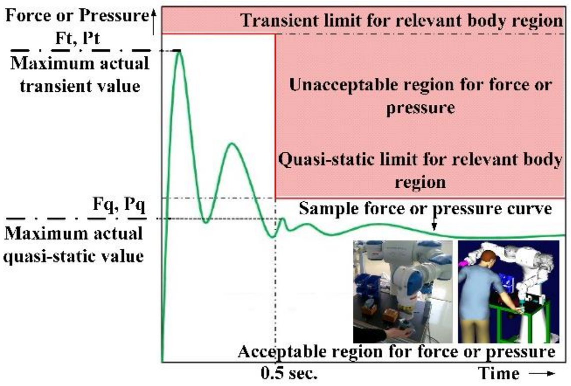

Figure 4. The example of quasi-static contact at the automated assembly process [ISO / TS 15066 2016]

The curve shown in Figure 4 provides the trend of force and pressure within the onset pain limit. ISO / TS 15066 collects the admissible pressures and forces for 29 human body areas for both the transient and quasi-static contact types. Moreover, it also provides a correlation between the speed limit and mass of the robotic system for the maximum allowed energy transfer of an operator's body region. Risk reduction that comes from quasi-static contact should be limited by:

A. *Prevent the occurrence* of areas with crushing and shearing points.

B. *Ensure the resilient design* of the robotic system and whole workplace parts.

C. *Optimisation of the robotic arm path* (exception body and head regions).

D. *Reduced dynamics* (torque, force, speed, power).

E. *Restricted collaboration space*.

F. *Optimisation of robotic arm path* – prevent violent movements by programming.

G. *Traversing movements* must be downwards where possible.

Biomechanical limit criteria for transient and quasi-static contact are under development. Table 2 (extracted from ISO / TS 15066) provides the quasi-static impact force measurement for upper limbs.

Body region	**Specific body area**		**Quasi-static contact**	
			Peak pressure p_s [N/cm²]	**Force [N]**
Hands and fingers	17	Forefinger pad D	298	135
	18	Forefinger pad ND	273	
	19	Forefinger end joint D	275	
	20	Forefinger end joint ND	219	
	21	Thenar eminence	203	
	22	Palm D	256	
	23	Palm ND	260	
	24	Back of the hand D	197	

Table 2. Quasi-static impact force measurement for upper limbs [ISO / TS 15066 2016]

5 CONCLUSIONS

The article aims to address the main challenges in power and force limiting techniques in collaborative robotics. Its addressing points out the necessary safety measures of possible contacts (transient, quasi-static) at the automated workplaces. Also, part of it is categorization, technical standards (ISO / TS 15066) with an impact on their awareness. The predispositions of these collaborative workplaces come from their higher flexibility in the (automotive) production required to respond at varying production volumes and customized product demands. As shown in the example of the automation of the assembly process by human and robotic systems, the technical specification ISO / TS 15066 list with maximum forces (thus pressure) must be considered. A wide range of applications produces different feel an abnormal force being exerted on its body by inherent design and control. So, this fact should be taken into account; the robotic system only imparts limited static and dynamic forces.

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