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Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments

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ABSTRACT After many years of rigid conventional procedures of production, industrial manufacturing is going through a process of change toward flexible and intelligent manufacturing, the so-called Industry 4.0. In this paper, human–robot collaboration has an important role in *smart factories* since it contributes to the achievement of higher productivity and greater efficiency. However, this evolution means breaking with the established safety procedures as the separation of workspaces between robot and human is removed. These changes are reflected in safety standards related to industrial robotics since the last decade, and have led to the development of a wide field of research focusing on the prevention of human–robot impacts and/or the minimization of related risks or their consequences. This paper presents a review of the main safety systems that have been proposed and applied in industrial robotic environments that contribute to the achievement of safe collaborative human–robot work. Additionally, a review is provided of the current regulations along with new concepts that have been introduced in them. The discussion presented in this paper includes multidisciplinary approaches, such as techniques for estimation and the evaluation of injuries in human–robot collisions, mechanical and software devices designed to minimize the consequences of human–robot impact, impact detection systems, and strategies to prevent collisions or minimize their consequences when they occur.

INDEX TERMS Safety, industrial robot, human-robot collaboration, industrial standards, Industry 4.0.

I. INTRODUCTION

In the last 50 years industrial robots have been widely used in the manufacturing industry, and they have substituted humans in various tasks, relieving workers from repetitive, unhealthy or dangerous jobs. A direct result of the deployment of robots in industry is the rise of new risks of accidents for workers. The industrial regulations that incorporate these robot related risks for workers include the international standard ISO 10218 and the Technical Specification ISO/TS 15066:2016, the American ANSI/RIA R15.06, the European EN 775 which is adapted from the ISO 10218, and national standards such as the Spanish UNE-EN 755 which is adapted from the EN 755 by the Spanish Association of Normalisation and Certification. To prevent accidents the selection of a safety system must be based on the analysis of the aforementioned risks. Commonly in the past, safety systems have separated the robot and human workspaces. One instance of this separation was reflected in the standard UNE-EN 755:1996 [1] which established that sensor systems had to be incorporated to prevent the entrance of persons in a hazardous area, where the operating state of the robotic system could have caused dangers to the workers. According to traditional standards, authorised personnel can only be inside the robot workspace if the robot is not in automatic mode.

The pursuit of more flexible and more efficient manufacturing is driving significant changes in industry. The transformation from automatic manufacturing to Industry 4.0, which has been predominantly promoted from Germany, or to smart factories fostered from the USA [2], is based on the emergence of a new generation of systems that introduce the latest technological advances in information and communication technologies (ICTs), data analysis, and devices such as sensors or robots. These transformations are causing that the tasks performed by industrial robots are no longer restricted to the transfer of objects, or other repetitive actions. Instead, there is an increasing number of tasks in which humans and robots combine their skills in collaborative work.

To facilitate effective collaborative work between a human worker and an industrial robot, previously existing barriers that established a inflexible separation between human and robot workspaces need to be eliminated. Instead, other types of safety systems need to be introduced, so that collisions can be prevented by detecting obstacles as well as their motion, applying appropriate avoidance strategies, and harm to the human can be minimized in case of an unexpected or unavoidable impact. These changes in work practices in industrial environments are reflected in the updates that have appeared from the year 2006 in the the ISO10218 standard [3], and the guidelines for the implementation of these regulations, such as [4]. In these updates new concepts are introduced, including the concepts of *collaborative operation*, *collaborative workspace*, and *collaborative robot*, which are of direct relevance to this review.

The latest update of the standard ISO 10218-1 [5], and ISO 10218-2 [6] is focused on the above definitions, providing details on *collaborative operation requirements*, and *cooperation task typologies*. The former includes for instance start-up controls, functioning of the safety control system, motion braking, speed control, while the latter includes for example manual guidance, interface window, and cooperative workspace.

The international standard ISO: 8373-2012 [7] specifies the vocabulary used in relation to robots and robotic devices. Here, new terms involved in the development of new collaborative tasks in industrial and non-industrial environments are defined, such as *human-robot interaction* and *service robot*, in addition to more established terms, such as *robot* and *control system*.

The recent Technical Specification ISO/TS 15066:2016 [8] attempts to further specify human-robot collaboration by supplementing the requirements and guidance established in ISO 10218.

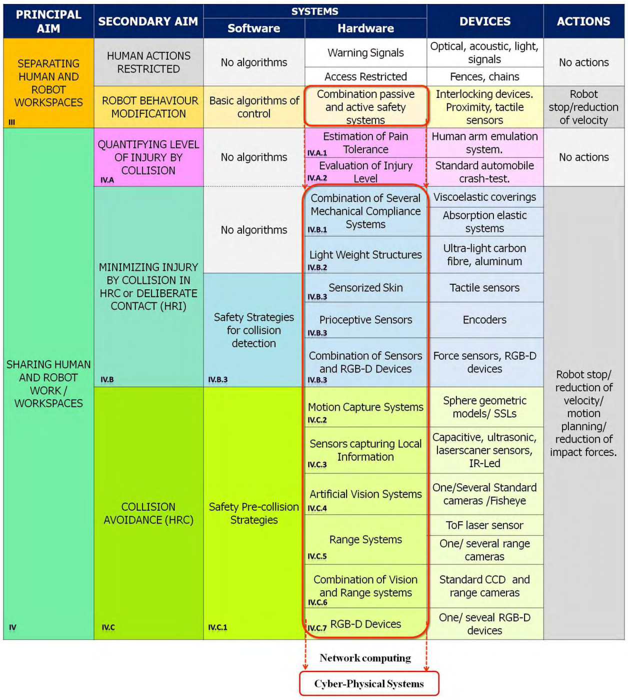
The way the standards have evolved in the last decade reflects the current trend towards what many researches have called *human-robot collaboration* (HRC) in an industrial context. Although other types of robots that perform collaborative tasks with humans have been developed within the last few decades (e.g. social robots, assistive robots and haptic devices), these robots have different purposes from those of the industrial robots used for manufacturing and are therefore not discussed in this review.

Previous review articles in the area of safety in human-robot collaboration have been published [9]–[11]. This article provides contributions beyond the previous reviews by covering the latest standards in robot safety and reviewing the latest safety systems, including light robots, motion capture systems and simulated environments, the use different types of cameras, and techniques for the fusion of visual information. Moreover, this article reviews ways of fitting robot safety within the framework provided by Cyber-Physical Systems.

II. A FRAMEWORK FOR SAFETY IN INDUSTRIAL ROBOTIC ENVIRONMENTS

To provide a structured framework for further discussion in this article, a classification of the main safety systems in robotic environments is provided in Table 1, including the aims pursued by the safety systems, hardware and software systems that are employed, devices that are used, and the actions involved in each type safety system. Table 1 indicates the sections of the paper where each subject is covered.

TABLE 1. **Classification of safety in industrial robot collaborative environments.**



PRINCIPAL AIM	SECONDARY AIM	SYSTEMS		DEVICES	ACTIONS
		Software	Hardware		
SEPARATING HUMAN AND ROBOT WORKSPACES III	HUMAN ACTIONS RESTRICTED	No algorithms	Warning Signals	Optical, acoustic, light, signals	No actions
			Access Restricted	Fences, chains	
	ROBOT BEHAVIOUR MODIFICATION	Basic algorithms of control	Combination passive and active safety systems	Interlocking devices. Proximity, tactile sensors	Robot stop/reduction of velocity
SHARING HUMAN AND ROBOT WORK / WORKSPACES IV	QUANTIFYING LEVEL OF INJURY BY COLLISION IV.A	No algorithms	IV.A.1 Estimation of Pain Tolerance	Human arm emulation system.	No actions
			IV.A.2 Evaluation of Injury Level	Standard automobile crash-test.	
	MINIMIZING INJURY BY COLLISION IN HRC or DELIBERATE CONTACT (HRI) IV.B	No algorithms	Combination of Several Mechanical Compliance Systems IV.B.1	Viscoelastic coverings	Robot stop/ reduction of velocity/ motion planning/ reduction of impact forces.
				Absorption elastic systems	
			Light Weight Structures IV.B.2	Ultra-light carbon fibre, aluminum	
		Safety Strategies for collision detection IV.B.3	Sensorized Skin IV.B.3	Tactile sensors	
			Prioceptive Sensors IV.B.3	Encoders	
			Combination of Sensors and RGB-D Devices IV.B.3	Force sensors, RGB-D devices	
	COLLISION AVOIDANCE (HRC) IV.C	Safety Pre-collision Strategies IV.C.1	Motion Capture Systems IV.C.2	Sphere geometric models/ SSLs	
			Sensors capturing Local Information IV.C.3	Capacitive, ultrasonic, laserscaner sensors, IR-Led	
			Artificial Vision Systems IV.C.4	One/Several Standard cameras /Fisheye	
			Range Systems IV.C.5	ToF laser sensor	
				One/ several range cameras	
			Combination of Vision and Range systems IV.C.6	Standard CCD and range cameras	
			IV.C.7 RGB-D Devices	One/ seveal RGB-D devices	

In addition to such elements, the term of Cyber-Physical Systems (CPS) has been included due to the recent developments in intelligent manufacturing have important implications on the implementation of robot safety systems. In this way, the incorporation of network computing, connected devices and data management systems in manufacturing processes, including active safety systems, have resulted in instances CPS. Cyber-Physical System are defined as physical devices which are provided with technologies to collect data about themselves and their surroundings, process and evaluate these data, connect and communicate with other systems and initiate actions to achieve their goals [2], [12].

The use of the CPS framework in the manufacturing industry has helped to bring the sharing of workspaces between humans and robots from concept to reality. This has contributed to achieving a flexible, adaptable, reliable and high performing production. CPS can be considered as a living concept from which variations such as *Cyber Physical Production Systems* (CPPS) are emerging [13]. CPPS is seen as a more specific concept that is geared to manufacturing [14], and not as a generalist as CPS which covers areas so diverse as transport, infrastructure, health care, emergency response, defence, energy, or manufacturing.

Taking into account that, along with other applications, safety issues fall within the scope of Cyber Physical Systems (CPS), in [15] safety systems based on CPS for a human-robot collaboration team were implemented. For this purpose, several safety approaches, which allow to have different levels of HRC, have been proposed. For each proposed strategy, different types and combinations of sensors are used including laser scanners, proximity sensors, vision systems, or force sensors. The results show that there are technological limits on the sensor data rates and the number and type of feasible sensors used in the implementation of the system. These drawbacks highlight the technological limits and challenges associated with the real-time implementation of CPS applied to human-robot collaboration.

In the context of intelligent manufacturing where all devices are interconnected share information and make decisions and perform actions, safety is closely bounded up with security. In the understanding that the concept of security is related to threats or cyber attacks that CPS can suffer, the possible interdependences between safety and security should be taken into account to achieve a more robust hazard management, as analysed in [16].

Another important aspect to achieve effective and safe co-working in smart factories is the psychological state of the operator. It is necessary to ensure that the operator feels comfortable and safe when cooperating with a robot, and that mental strains associated with such tasks are bearable. In [17] an assessment of mental strains of a human operator working in a cellular manufacturing system was carried out through experiments in which three influential factors in operator mental strain, including distance, speed and warnings of motion, were varied in order to define design criteria to improve operator comfort.

Suitable operator training clearly has an influence on their confidence and stress levels as well as their safety as is suggested by experimental results in [18] and [19], and this is reflected in documents such as the guidelines for implementing ANSI/RIA/ISO [4], and in standard ISO/TS 15066:2016 [8]. Training can be considered as a safety measure that does not depend on specific technologies being used in robotic systems, thus falling out of the classification of Table 1.

III. SEPARATING HUMAN AND ROBOT WORKSPACES

Typical industrial robots are large, heavy and move at high speeds. These circumstances make it necessary to prevent impacts between the robot and a human who may enter the robot workspace, so as to avoid harm to the human. The approach prescribed by the previous standard ISO 10218:1992 or its equivalent UNE-EN 775 [1] to prevent such collisions or other incidents that may result in injuries, was to establish a compulsory separation between human and robot workspaces, by detecting human intrusions in robot workspaces, and modifying the robot behaviour accordingly. Based on these restrictions, an implementation of this kind of working environment is presented in [20]. When an intrusion into the robot workspace is detected the robot speed is reduced in proportion to the detected hazard level, with the robot stopping its movement at the highest one. Three levels of hazard detection are proposed along with control strategies, passive and active safety devices. Such devices include for instance acoustic signals, proximity sensors, pressure mats, and ultrasonic sensors. Fig. 1 shows the layout of the separation of human-robot workspaces using active and passive devices proposed in [20].

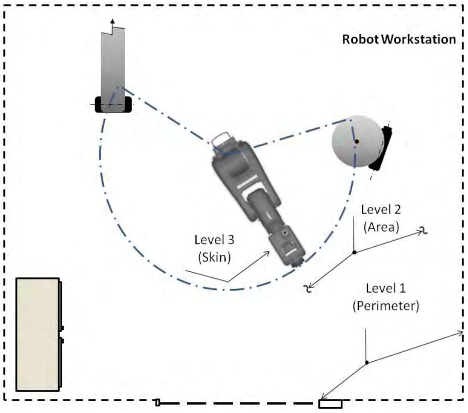


FIGURE 1. Separating human-robot workspace. A drawing based on [20].

IV. SHARED HUMAN AND ROBOT WORK/WORKSPACES

As discussed above, collaborative tasks involving human and robot make it necessary to remove the separating elements between them, and therefore new risks emerge that need to be addressed. In the following sections the main approaches to mitigate these risks are presented, including the quantification level of injury by collision. The information about the consequences to the human body of having a collision with a robot is key in taking the necessary steps to minimize injuries to the human and can be used for testing new robot safety systems.

A. QUANTIFYING LEVEL OF INJURY BY COLLISION

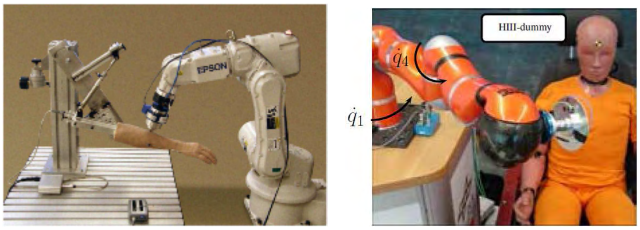
Focusing on systems whose principal aim is to enable safe human robot collaboration, several researchers have analysed the consequences of human-robot collisions on the human body. This question may be approached from two different points of view. The first one is to estimate the pain tolerance, and the second one is to quantify the level of injury following a collision.

1) ESTIMATION OF PAIN TOLERANCE

Different methods have been studied to estimate the level of pain that can be tolerated by human in a robot-human collision. A study focused on the evaluation of the human pain tolerance limit is described in [21]. The study was based on the use of an actuator consisting of a pneumatic cylinder delivering impacts to 12 parts of the body of human volunteers to find a value of tolerable contact force.

The authors suggest further analysis of human pain tolerance as simulations showed that if a conventional robot with a stiff surface was used, the value of impact force could easily transcend the acceptable threshold at common operating velocities, even when a compliant covering was employed.

An alternative to the participation of volunteers in human pain tolerance experiments is presented in [22], which attempts to evaluate pain by using a mechanical device to replace the human in the experiments. For this purpose, a passive mechanical lower arm (PMLA), which imitates the relevant human characteristics, was built and proposed to be used in dangerous experiments, Fig. 2(a). In this work, the perception of pain as well as the impact force, velocity and acceleration in robot-human collisions were evaluated using human volunteers and correlated with measurements obtained using the PMLA. The human subjects had to indicate the pain intensity they felt after each robot impact.



(a) (b)

FIGURE 2. **(a) The PMLA and a six-axis robot in [22]. (b) Impact experiments with a light robot LWRIII and a dummy [23].**

The authors found that the *impact energy density*, which is a function of the values of impact force, the contact surface area, and distance between the robot end-effector and the center of the PMLA, correlated well with the perceived pain. The authors concluded that this device is a sufficiently accurate emulation system when only the impact force and impact point speed are considered and evaluated, but not the impact point acceleration, and as consequence human volunteers could be replaced by the PMLA in such experiments.

2) EVALUATION OF INJURY LEVEL

Many studies into the collision between an industrial robot and the human body have made use of the injury criteria that have been developed for crash-tests in the automotive industry.

It should be noted that automobile crashes can affect the whole of the human body, therefore, to properly evaluate injuries, automobile crash-tests subdivide the human body into several areas. The body regions that have been defined by the AAAM [1] are head, face, neck, thorax, abdomen, spine, upper extremities and lower extremities [24]. Consequently, in order to evaluate injury at the totality of the human body, specific indices of injury for each body region have been developed, such as the Head Injury Criterion (HIC) [25]. The HIC is a means to evaluate head injuries following car collisions that has become one of the most used injury indices in industrial robotics settings. An equivalent division of body areas and their related indices were defined by the EuroNCAP[2] [26].

Furthermore, with the purpose of defining a numerical measure of the level of injury and making it possible to rank injuries resulting from motor vehicle crashes according to their severity, the Abbreviated Injury Scale (AIS) was proposed by the AAAM [24]. This scale provides a classification of injuries by body region according to their relative importance, and it provides six categories from *AIS-1* (minor injury) to *AIS-6* (maximal injury which can be considered as fatal). In cases when several regions of the body are injured, the Maximun Abbreviated Injury Scale (MAIS) is applied, such that the area with maximum injury severity is used to define the overall injury severity.

Standard injury indices developed by the automotive industry have been employed in human-robot collisions as a way to assess the effects of these impacts on the human body.

From the aforementioned body regions proposed by the automotive industry, the head area has been of particular interest in the analysis of human-robot collisions. For this reason, the HIC index has been widely used as a tool to evaluate the qualities of experimental robotic safety systems [27]–[33]. This index considers both collision duration and the head acceleration response during the collision. Two commonly used collision intervals have been used in the robotics literature: 15 and 36 milliseconds [34], [35]. Therefore, depending on the interval of time used, the HIC_{15} and HIC_{36} indices, corresponding to 15 and 36 milliseconds respectively, are commonly employed. Other researchers have considered the use of indices that measure injuries to the head, torso and neck regions, respectively, to evaluate injuries following human-robot collisions [9], [11].

Even though the AIS and MAIS indices are categorical and therefore have no associated numerical scale to measure injuries [35], some empirical relationships between the AIS (or MAIS) categories and HIC have been proposed [11], [35], [36].

Nevertheless, some researchers have questioned the suitability of using injury indices developed by the automotive industry in a robotics context. In [37], impacts between a robot and the head, chest and pelvis of a dummy have been evaluated by means of a computational robot-dummy crash simulator. This work concludes that the use of classical severity indices developed by the automotive industry is not suitable for the assessment of injuries resulting from robot-human collisions, and that new criteria should be proposed.

The adequacy of using injury indices developed by the automotive industry, including the HIC, in the human-robot collision context has been experimentally assessed

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[1] Association for the Advancement of Automotive Medicine

[2] European New Car Assessment Programme

in [23], [36], and [38]. Based on these works, the research described in [35] provides descriptions and mathematical formulation of relevant injury classification metrics and biomechanical injury measures for head, chest, neck and eye. In addition, the European testing protocol EuroNCAP was applied experimentally in unconstrained and constrained impacts to the head, chest and neck using different robots, including a light robot LWR-III, illustrated in Fig. 2(b).

The conclusions in [35] claim that the resulting EuroNCAP index values do not exceed the safety thresholds and thus severe injuries are unlikely to occur, since the maximum speeds reached by robots are considerably lower than typical car speeds, concluding that HIC and similar criteria are apparently not suitable to be applied in robotics. However, at low robot speeds, some severe injuries, such as fractures of facial and cranial bones, can result, and therefore require the setting of appropriated injury indices.

Table 2 shows injury indices commonly used to assess robot-human collisions, according to the body area of focus, along with references from the literature where the specific indices are mentioned or employed.

TABLE 2. Injury indices used to assess robot-human collisions.

BODY AREA	INJURY INDEX	REFERENCES
Head area	WSTC (Wayne State Tolerance Curve)	[9], [10], [11], [28], [35], [36]
	HIC (Head Injury Criterion)	[9], [10], [11], [23], [27], [28], [29], [30], [32], [33], [34], [35], [36], [37], [38]
	3ms-Criterion	[10], [28], [35], [36], [38]
	GSI (GADD's Severity Index)	[10], [27], [28], [38]
	MPI (Maximum Power Index)	[9], [11], [35], [38]
	MSC (Maximun Mean Strain Criterion)	[9], [11], [35], [38]
Chest area	VC (Viscous Criteria)	[10], [23], [28], [35], [36], [37], [38]
	Compression Criterion	[9], [11], [23], [35], [36], [38]
	Force Based Criterion	[9], [11], [23], [35]
	Acceleration Criterion	[11], [35], [38]
	TTI (Thoracic Trauma Index)	[10], [28]
Neck area	NIC (Neck Injury Criterion)	[9], [11], [35], [36]

The recent standard ISO-TS 105066:2016, clarify the appropriate procedure for limit speed values that maintain force and pressure values under the pain sensitivity threshold in human-robot contacts. Based on research reported in [21], [39], and [40], this standard defines 12 areas for testing the human body, Fig. 3, along with the maximum permissible pressure and force values, formulas to obtain the maximun permissible energy transfer for each body area, and the corresponding speed limit values for transient contact between a human body and a part of a robot system. It should be noted that the standard states that contact with the face, skull, forehead, eyes, ears, and larynx areas is not permissible.

B. MINIMIZING INJURY IN HUMAN-ROBOT COLLISION

As in some cases a robot-human collision during the execution of collaborative tasks can be unavoidable, an important line of research focusses on the minimization of injuries in humans caused by such collisions. The methods that have been proposed to reduce the effects of collisions can be broadly classified as *mechanical compliance systems* and *safety strategies involving collision/contact detection.*

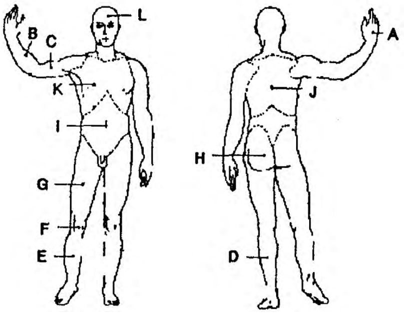


FIGURE 3. Measurement points for human-robot impact, [21].

1) MECHANICAL COMPLIANCE SYSTEMS

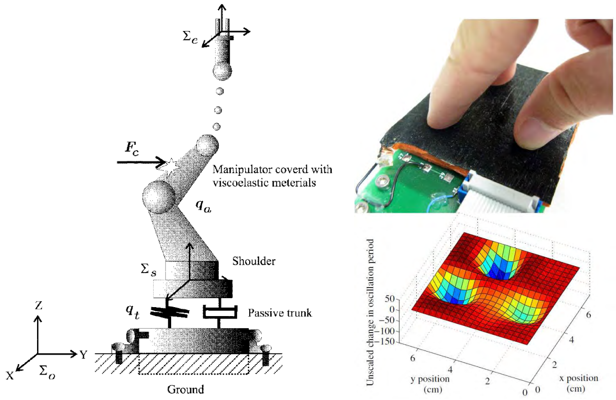
Mechanical compliance systems aim to reduce the collision energy. On the basis of this idea, several mechanical systems such as viscoelastic coverings, absorption elastic systems, safe actuators, or light weight structures, have been proposed. These systems can be used in combination with each other, and along with systems and strategies for collision detection/avoidance.

a: VISCOELASTIC COVERING

A safety system for robot-human interaction is proposed in [21] in which the robot is equipped with torque sensing and links which are covered with a viscoelastic material. This cover aims to reduce impact force whilst maintaining contact sensitivity. The authors found that although the use of soft compliant rubbers or urethane foam allows to mitigate collision forces, the achieved reduction is not sufficient to ensure that pain tolerance thresholds are not exceeded. A robot stop function is then activated as soon as a human-robot contact is detected. This stop function allows to maintain human safety even when the robot makes an unexpected contact with the person during a cooperative task.

In [43], the work focusses on the analysis of faults in human-robot coexistence systems. Aiming to remove all hazardous elements around the robot links, viscoelastic coverings around the link surfaces are also used, in addition to mechanical measures such as the use of spherical joints to prevent mechanical shearing, and mechanical stoppers to limit the motion range of each joint.

Viscoelastic coatings are also used as a suitable component for contact force reduction in [41], along with a deformable trunk consisting of springs and dampers, which is located between a fixed base and the robotic arm, see Fig. 4(a). This kind of *absorption elastic system*, which is further discussed below, provides passive redundant degrees of freedom helping to avoid impact forces of excessive magnitude. The article concludes that most traditional industrial robots are difficult



(a) (b)

FIGURE 4. **(a) Conceptual model of an Human Friendly Robot *HFR*, [41] (b) Tactile display from the capacitive array prototype, [42].**

to use in human-robot collaboration because of their large inertia and weight, thus the use of a light robot with low inertia, in combination with a soft surface, is recommended. The development of light robots based on light weight structures and their use in human-robot collaboration is discussed below.

The evolution of viscoelastic covering towards having capabilities for sensing the location of contact with objects is treated in [44]. The development of tactile skin coverings has been investigated as a means to enhancing collaborative human-robot work in [42], where a low-noise capacitive force sensing array embedded in the soft foam that covers the whole body of a manipulator was proposed, as illustrated in Fig. 4(b). Their results reveal that this sensor array enables force or contact control in collaborative manipulation tasks, while the soft cover helps with energy absorption in case of impact.

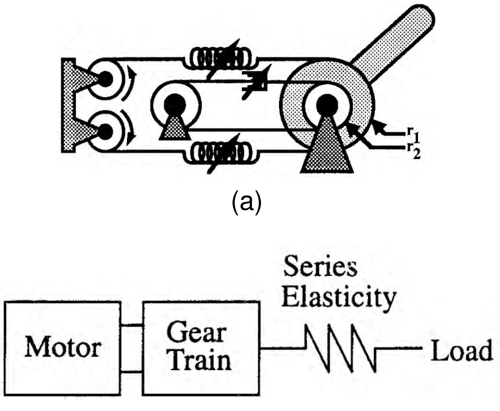
The use of superficial tactile sensors in the skin covering is treated in section IV-B3 as a way to obtain information about intentional or unintentional human-robot contact and then triggering a suitable collision reaction strategy.

b: MECHANICAL ABSORPTION ELASTIC SYSTEMS

As mentioned above, the use of absorption elastic materials and systems in industrial robots is one of the solutions that have been proposed to enhance safety during interactive tasks between humans and robots. These components are able to absorb part of the energy in a human-robot impact but not enough to effectively reduce injuries to the human. Therefore, several mechanical solutions which provide the robot arm with compliant behaviour have been proposed. These solutions are discussed below.

The traditional stiff actuators used in industrial robots normally introduce a high impedance. This characteristic is required to accomplish the precision, stability and bandwidth required for accurate position control, such that the higher the stiffness, the better the behaviour. However, a high stiffness is not desirable from a safety point of view, since it introduces several disadvantages in collision situations. These disadvantages include lack of compliance, friction, backlash, and increasing reflected inertia, among other issues which result from using gear reduction in electric motors, [46]. Therefore, with the aim of achieving a compromise between precision and safety, the implementation of mechanical compliance using elements such as springs and dampers has been explored in various works giving rise to different solutions. A brief description of the most popular of these approaches is provided below.

One approach to design a compliant actuator is the *Programmable Passive Impedance* (PPI) whose development is described in [45], which performs interactive tasks through flexible motion, see Fig. 5(a). The idea is to control the impedance of a robot by adding programmable mechanical elements into the drive system. To implement the programmable passive impedance, a binary damper and antagonistic nonlinear springs with programmable damping and stiffness coefficients, were designed and employed. Nevertheless, according to [47], this solution does not provide sufficient accuracy when controlling the end-effector position or force because the antagonistic motors need to operate in synchrony. Therefore, with the aim of adjusting the joint impedance, a mechanism called *Mechanical Impedance Adjuster* (MIA) consisting of a joint-driver, a pseudo-damper and a compliance adjuster was proposed in [47]. This approach was evaluated on a prototype arm model and was shown to provide the desired level of compliance.

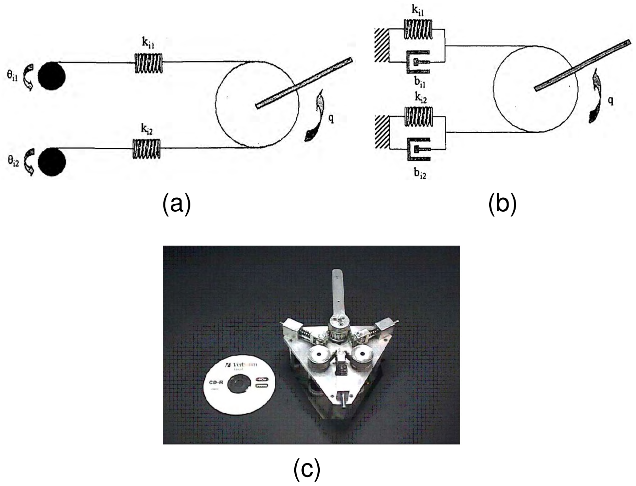


(a)

(b)

FIGURE 5. **a) A single-link manipulator using the PPI mechanism (binary damper and non-linear spring) [45]. b) Block Diagram of SEA [46].**

Bicchi *et al.* [48] report the use of the idea of varying the stiffness transmission in a new concept named *Variable Stiffness Transmission* (VST), which allows the passive compliance to be modified while the robot is functioning. The implementation proposed in [48] is set up using two nonlinear actuators that are connected to a joint in a agonistic-antagonistic configuration through mechanically compliant elements, which can be conical (nonlinear) springs, Fig. 6(a). This configuration allows to control joint position and stiffness independently. However, this solution has some difficulties in achieving springs with a suitable elastic characteristic.



(a) (b)
(c)

FIGURE 6. **a) VST antagonistic springs [48]. b) VST antagonistic McKibben motors [48]. c) Prototype of VSA proposed by [49].**

An alternative implementation is to use two antagonistic McKibben actuators instead of the combination of non-linear actuators and compliant elements, Fig. 6(b). This idea was later implemented and tested [28], demonstrating the high flexibility and effectiveness of VST using McKibben actuators.

Based on the VST principle, the concept of *Variable Stiffness Actuators (VSA)* along with the design of a prototype is presented in [27]. This mechanism consists of three pulleys arranged in a triangle over which a timing belt is placed. Two of the pulleys are controlled each by a servomotor. The third pulley is connected to the arm. The two tensioning mechanisms located close to the pulley coupled to the arm form the non-linear springs. The other tensioning mechanism keeps the tension of the belt against the other two pulleys. An effective control approach for the VSA, Fig. 6(c), is presented in [49].

The proposed approach is geared to independently controlling joint positions and stiffness. Experimental results show that the variation of transmission stiffness helps to keep injury risk within safe levels during the execution of trajectory tracking tasks. It is worth pointing out that the concept of Variable Impedance Actuators (VIA), which is used in various searches (e.g. [30], [49]), can be considered equivalent to the concept of compliant actuator [50], [51].

An alternative design, which attempts to mitigate the disadvantages of an increased inertia and high back-drive friction of gear trains in gear-head actuators, is the compliant device known as *Series Elastic Actuator (SEA)*, which is proposed in [46] and is illustrated in Fig. 5(b). This approach uses a passive mechanical spring in series between the output of the actuator (the gear train) and the load (the robot link). The benefits that these drivers can provide are shock tolerance, lower reflected inertia, more accurate and stable force control, less damage to the environment, and energy storage. However, according to [29], [52], and [53] SEA is not suitable for the high-bandwidth control that is required in some tasks that demand fast dynamics. Moreover, SEA keeps the impedance constant, thus becoming unsuitable for tasks that require different impedance values.

Benefiting from the advantages SEA, this actuator was used in the *Distributed Elastically Coupled Macro Mini Actuation (DECMMA)* approach [52], later also termed as *Distributed Macro-mini Actuation* DM^2 [29]. DM^2 is geared to reach the joint torque characteristics equivalent to those of a zero gravity robot arm which are required for decreasing uncontrolled impact loads. These work conditions are produced dividing the torque generation into low and high frequency torques (run through manipulation tasks and disturbance rejection respectively). The relocation of the major actuation effort from the joint to the base of the robot through the location of low frequency actuator (SEA) at the base of the robot, where high frequency torques are not required, accomplishes the reduction of the inertia, as well of the weight, of a robotic arm. Besides, the high frequency torques are achieved by placing a high frequency actuator at the joint and using a low inertia servomotor. In [53] the effectiveness of the DM^2 approach in reducing the impact loads associated with uncontrolled robotic arm collision was tested by simulation and experimentally verified using a two-axis prototype robotic arm that incorporated this structure.

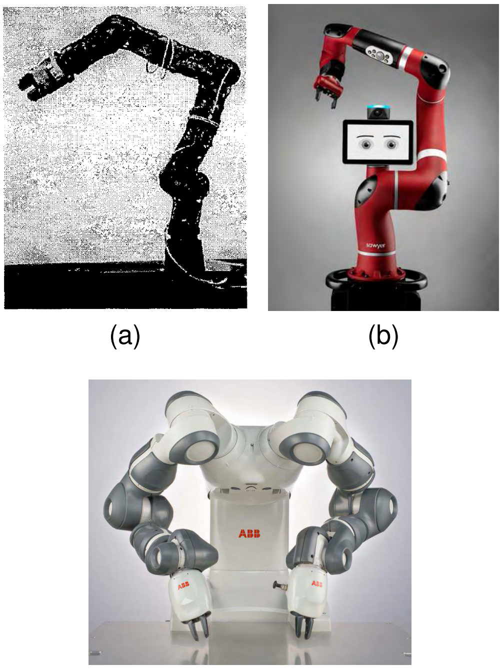
One alternative to the above implementation is to replace the series elastic component between the actuator and the load by a MR (magneto-rheological) fluid damper. In [54] the force control actuator known as *Series Damper Actuator* (*SDA*) was proposed, experimentally developed, and analysed, demonstrating to be an effective force/torque control actuator. Based on the use of MR links, the development of the actuation approach called *Distributed Active Semi-active Actuation* (*DASA*) is discussed in [33]. This actuation approach, which is aimed at systems interacting physically with humans, uses MR clutches for coupling the motor drive to the joint instead of using mechanical compliance, achieving a instant reduction of the effective inertia of the link. This characteristic seems to improve the manipulator performance and also the manipulator operation at higher velocities, maintaining safe HIC values.

Some of the mechanical absorption elastic systems discussed above have resulted in successful devices used in commercial industrial robots as is shown next, under *Light weight structures*. Further details on the absorption elastic systems discussed above as well as other similar approaches are discussed in [50], [51], and [55].

2) LIGHT WEIGHT STRUCTURES

In the 1990s the first generation of light weight robots (LWR) was presented by the Institute of Robotics and Mechatronics at DLR. This robot was an evolution of a previous version developed at the beginning of the decade for training astronauts due to their need for a light and flexible robot [70]. The design concept and first steps towards a light weight robot generation were presented in [71] and [72].

The goal was to design a multi-sensory, modularly configurable light weight robot in a unified and integrated way. Later, control approaches were reported in works such as [73] and [74], where experimental and/or simulation results for different control strategies for the DLR lightweight robot were provided. Further developments resulted in the second generation of lightweight robots [69], [75], Fig. 7(a). The third generation LWRIII was presented in 2002 [76]. In 2004, DLR transferred this technology to the KUKA Robot Group [77], [78], where several robot generations were developed, from KUKA LBR3 [79] to LBR iiwa [56].


(a) (b)

(c)

FIGURE 7. **(a) DLR II in [69]. (b) Baxter-Sawyer in [59], ©Rethink Robotics. (c) Yumi in [66], ©ABB.**

With the development of systems for mechanical compliance, such as the VSA approach [80], [81], the SEA approach [82], decoupling the heavy motor inertia from the link inertia [53], [59], the use of lightweight materials such as light carbon fibres [68], [76], and the use of sensor skin based on capacitive sensing developed by MRK-Systeme for Kuka robots [83] or the capacitive skin developed by Boch for the APAS robot [64], the robots listed in Table 3 are suitable for collaborative human-robot tasks. These robots have been the basis of many investigations into quantifying the level of injury by collision discussed in section IV, minimizing injury in human-robot collision described in section IV-B, the development of safety strategies for collision/contact detection in section IV-B3, and using RGB-D devices to avoid impacts in collaborative tasks discussed in section IV-C7.

TABLE 3. **Commercial light robots.**

ROBOT	COMMERCIAL GROUP	REFERENCES
LBR iiwa	KUKA	[56]
UR family	Universal Robots	[57]
WAM	Barrett Tecnology	[58]
Sawyer and Baxter	Rethink Robotics	[59]
AUBO-i5	AUBO Robotics	[60]
CR-35*i*A	FANUC	[61]
ROBERTA	Gomtec	[62]
LWA 4P	ROBOTNIK	[63]
APAS	Bosch	[64]
FRIDA and YUMI	ABB	[65],[66]
SDA20D	YASKAWA	[67]
JACO and MICO	Kinova	[68]

Traditional robot arms can be equipped with some of the safety systems discussed in this paper to make them more suitable for sharing work or workspaces with a human operator. For specific manufacturing processes that require collaboration or interaction between human and robot, the characteristics of light weight robot arms make them much more suitable than traditional robot arms. In fact, current commercial light weight robots already incorporate many of the safety features discussed in this paper which are very important for safe human robot interaction.

Apart from the enhancement in safety issues, the use of these robots in industry presents favourable benefits in terms of energy efficiency. According to [84], given that light robots are provided with energy-saving features, their use contributes towards energy savings in industrial manufacturing. This is an important issue since the optimization demanded in Industry 4.0 also aims to decrease energy consumption in manufacturing processes.

3) SAFETY STRATEGIES INVOLVING COLLISION/CONTACT DETECTION

To increase the effectiveness of systems dedicated to minimizing injury in human-robot collisions, mechanical systems are often linked to safety strategies involving collision detection which are applied during human-robot collaboration, or to safety strategies which allow deliberate contact between human and robot.

As previously discussed, safety systems are usually not used individually in industrial robots designed for collaborative work. Yamada *et al.* [85] present the combination of two phases of safety to allow human-robot contact by keeping the human pain within certain values of tolerance. The first phase relates to the study of human pain tolerance in human-robot collisions, which is based on [21] as discussed in Section IV-A1, and the use of viscoelastic covering as a means to mitigating impact consequences described above under *Viscoelastic covering*. The second phase decreases the velocity of the robot at the beginning of a human-robot collision. A distributed fail-safe contact sensor has been mounted on the robot link surface which provides information from the very onset of impact. This information is used to control the robot behaviour, reducing its velocity. In addition, a stop control function is also implemented and activated when required by the operating conditions. Experimental results using a 2-link manipulator show the effectiveness of decreasing velocity to achieve a tolerable human-robot contact.

The use of superficial tactile sensors in the skin covering is also treated in [86] as a way to obtain a faster triggering of a collision reaction strategy, without loss of the passive reduction of impact.

This idea of obtaining information from the impact point in a robot is currently under analysis. In [87] a conformable sensor skin made of optoelectronic components mounted on a flexible PCB was presented. This sensorized skin has the capability of measuring not only the position of the contact point but also the three components of the applied force, and thus it allows to estimate the force vector of the impact. The results of experimental tests on a light robot show a suitable behaviour of the robot in intentional and unintentional human-robot contact situations, with a controlled human-robot interaction and a safe reaction in case of accidental contacts being guaranteed.

A different approach is to use a mathematical model of the robot to mitigate the consequences of a collision. Focusing on reducing the impact force, a basic motion-planning/feedback-control algorithm, which relies on inertia reduction, passivity, and parametric path planning, was proposed in [88], where a conventional manipulator robot was used. This work shows that the inertia reduction controller enhances the safety of the robot and human working together by changing the apparent inertia of the robot by means of a simple adjustment of the common PD position control strategy.

De Luca and Mattone [89] avoid using dedicated sensors for human-robot collision detection by treating these events as a faulty behaviour of the robot actuating system. Robot actuator fault detection and isolation techniques are used to generate residual signals. Information of the components of the residual vectors allows to detect the link of the robot that has impacted and, to a certain extent, the contact force location and intensity. This information is used for developing a hybrid force/motion controller that manages what happens following the detection of a collision. Simulation results for a two-link planar robot were presented in this work. On the basis of this idea, in the work reported five collision reaction strategies were formulated and implemented on a light robot [90]. In the first strategy, the robot follows its trajectory without modifying its behaviour. In the second strategy, the robot is stopped at the time when the collision is detected. In the third strategy, the robot behaves in a very compliant way with zero-gravity torque reaction. The fourth strategy involves physical changes to the robot to make it lighter through the reduction of motor inertia and the link inertia. In the last strategy, the robot's behaviour involves getting away from the impact point. The assessment of the previously proposed collision detection and reaction strategies was carried out in [91]. The results show that the use of these techniques results in a decrease of forces keeping them below dangerous level to humans. Furthermore, the third an fourth collision reaction strategies where found to be very satisfactory for the operator because they feel that they have full control of the robot.

In [92] a unified system for safety in human-robot collaboration environments was proposed and successfully tested through experiments. Their main contribution is that the approach includes a collision detection and reaction algorithm that pulls the robot away from the collision zone, while allowing for intentional physical interaction. This algorithm is based on the use of residual signals proposed in [89]. The system also includes a collision avoidance strategy, which is based on the use of an RGB-D sensor. Moreover, the system employs a safe collaboration phase that allows both contactless interaction via voice and gesture recognition as well as the intentional physical contact between human and robot, which combines the residual method for collision detection with the localization of the contact point obtained from the RGB-D sensor.

In later work, Magrini *et al.* [93] introduce the concept of motion and force control at any contact point on the robot and provide generalizations of classical impedance and direct force control schemes, which are implemented without the need of a force sensor, relying instead on a fast estimation of contact forces, Fig. 8.

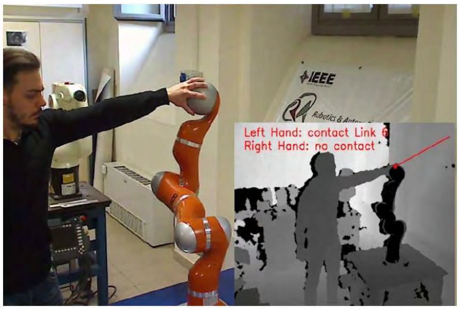


FIGURE 8. On-line estimation of contact forces [93].

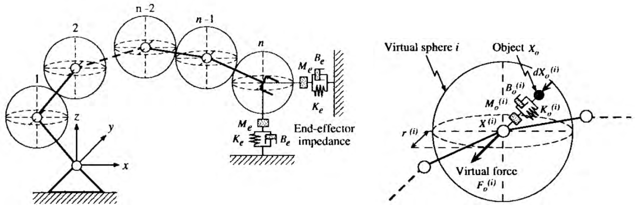
C. COLLISION AVOIDANCE

Although minimizing injuries in case of human-robot collision is very important, the prevention of impacts between robot and human is highly desirable. Therefore, a second key aim in human robot collaboration is to enhance safety through the implementation of collision avoidance systems. For this purpose, several solutions have been tried, which may be in many cases complementary to the previously discussed safety systems.

1) SAFETY PRE-COLLISION STRATEGIES

Although the idea of human robot collaboration emerged several years after the introduction of robots in the manufacturing industry, the avoidance of obstacles by robots has been a challenge from the beginning. Consequently, several methods for the estimation of the proximity from a robot to an object and the generation of alternative trajectories and acceleration/velocity variations before collision have been developed, and some of them are still used for strategies aimed at preventing undesirable robot-human impacts when human and robot are working together.

An example of such early work is [94] in which a real-time obstacle avoidance approach was based on the concept of *Artificial Potential Field*. The philosophy of the Artificial Potential Field is that the manipulator moves in a field of forces, where there are attractive poles for the end-effector (e.g. the position to be achieved), and repulsive forces (obstacles to be avoided). Another example is [95], which proposed an impedance control method based on visual information that is able to regulate a virtual impedance, establishing virtual spheres between robot and objects, Fig. 9.



(a) (b)

FIGURE 9. **[95] (a) Virtual spheres located on a link or a joint of the manipulator. (b) Virtual force as a function of virtual non-contact impedance at the *i*th sphere.**

The work described in [96] used danger estimates obtained in real time during HRC tasks to generate an alternative trajectory when the estimated danger index exceeded a pre-defined threshold. The danger index, which is based on [97], was defined as the product of the distance, velocity and inertia factors, and it was estimated for the nearest point between each link and the human, activating a suitable evasive action when the index exceeds a pre-defined threshold. Inspired by [94] and [95], the alternative trajectory generation relies on a *Virtual Force* that aims to push the robot away from the danger area. This virtual force is a function of the effective impedance at the closest point, and a function of the relative distance between the robot and the object.

To enhance this safety strategy a human monitoring system was added in subsequent work [98]. The information obtained from this human monitoring system during human-robot interaction was integrated into the safety system, which involves a safe path planner and a safe motion controller, to improve the safety of this operation. The monitored data includes physical features such as facial expression, head position, hand gestures or human eye gaze obtained from vision systems; or psychological features such as skin conductance, heart rate, pupil dilation, brain and muscle reactions. Results from the implementation of the integrated system in real-time human-robot interaction scenes reveal the efficacy of the proposed safety strategies.

The estimation of danger in the surroundings of the manipulator was also treated in [99], which introduced the concept of *Kinetostatic Danger Field* whose value decreases with the distance between the robot and a specific point in space and increases with linear link velocities. The position and velocity of the robot arm were measured through proprioceptive sensors and used to compute the danger field at any point of the workspace. Simulations carried out demonstrated the usefulness of the Kinetostatic Danger Field as a tool to improve safety strategies, since it helps to increase the level of safety in human-robot interactions.

In [100] a reactive control strategy that integrates the danger field concept with external information from the aforementioned distributed distance sensors (IV-C3), was implemented and experimentally validated. The reported results assert the benefit of the inclusion of the distance sensors to the robot's control system together with the reactive control strategy for enhancing human safety.

Other approaches use the concept of energy dissipation to propose an injury index to be integrated in a pre-collision control strategy [102], or to present a control algorithm that includes a safety indicator which is modulated by the distance between human and the end-effector of the robot [103]. In both cases experimental tests were carried out on lightweight robots.

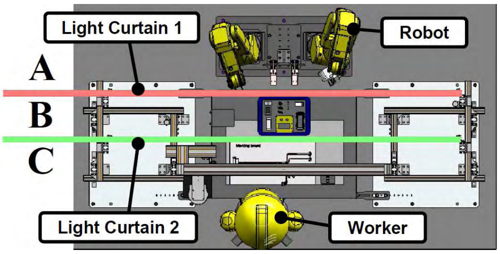


FIGURE 10. **Scheme of light curtains establishing three safety working areas in a cellular manufacturing operation, [101].**

A different approach based on the use of devices traditionally applied to isolate the robot from the human working area (photoelectric sensors and light curtains) to define three safety working areas is presented in [101]. The safety design for HRC in a cellular manufacturing was proposed and experimentally tested. With reference to Fig. 10, the safety strategy is as follows: in zone A, which is the closest area to the robots, high speed movements of the robots are allowed; in zone B, which is the intermediate zone, low speed movements are permitted; in zone C, which is the closest zone to the human, the robot speed is limited to be below 150mm/s and the restrictions in robot working area are applied, Fig. 10. To estimate the human posture and position an operator safety monitoring system receives from two IP cameras information from color marks on the head and shoulders of the human. Finally, the system checks the safety conditions and sends commands to the robot to ensure human safety.

Not only have camera systems [95], stereo camera systems [96], [98], [101], or IR-LED sensors [100] been applied in safety pre-collision strategies, but also devices that provide 3D information have been used as a means to evaluate distances between robot and human. For example, a real-time collision avoidance approach based on information captured from a RGB-D camera was presented in [104], where a method for estimating distances through the 3D data between robot and dynamic obstacles was presented, and later used in [92]. The distance values calculated were used to generate repulsive vectors that were applied as an input to a collision avoidance algorithm. The repulsive vectors obtained for each control point (the center of the spheres that model the robot arm) were employed to modify the robot motion at the control point of interest, obtaining smooth and feasible joint trajectories which prevent collisions. Two different approaches were considered to perform the motion control while executing the initial task. The first one, which is a variation of the artificial potential field method, focuses on the avoidance of collisions involving the end-effector. The second one aims to avoid collisions involving the robot body.

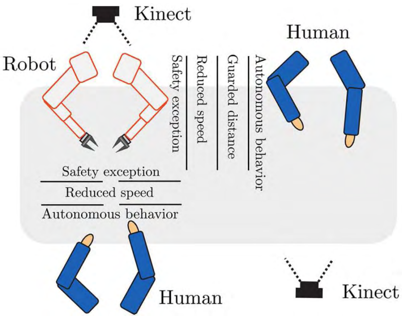


FIGURE 11. **Different robot's behaviours in experimental set-up for multiple HRC using RGB-D devices, [105].**

The control strategy presented in [105], which uses estimates of human-robot distances by monitoring the work area of a FRIDA robot using RGB-D cameras, aims to maintain the maximum level of productivity while enforcing human safety during collaborative work by defining various robot behaviours. Fig. 11 shows two cases in which a human is located on on side of the robot and in front of the robot, respectively. For the fist case, the robot operates with *autonomous behaviour*, keeping the programmed speed while no human is inside the workspace, but when a human enters the working area the robot turns to a *collaborative behaviour* in which the human-robot distance is monitored, such that when the human approaches the robot and some safety constraints are violated, the velocity of the robot is decreased. Furthermore, in case the human is too close to the robot, its behaviour turns to a *safety exception*, suspending the execution of the current task. Finally, when the human leaves the work area or the distance can be considered to be safe, the task is resumed. In the second case, when a human is working in front of the robot, the behaviours are similar to the previous case but the collaborative behaviour always involves a reduction of speed.

The following paragraphs are closely linked to the safety pre-collision strategies, and discuss the different devices used to capture information from the scene, and the way in which each type of information is treated for use in such strategies.

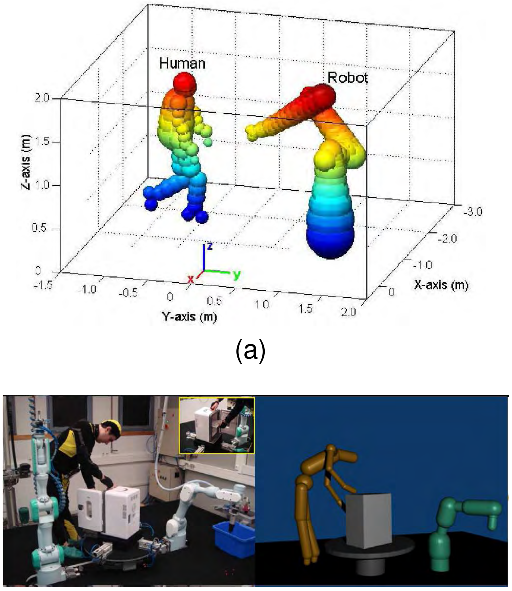
2) MOTION CAPTURE SYSTEMS AND SIMULATED ENVIRONMENTS

The workspace of a traditional industrial robot is at least partially unknown as there may be multiple changes taking place in the environment, such as changes in object or tool position, and the movement of human operators within the workspace. The analysis of such uncertain environments is a necessary but complex task which has been mainly approached in two ways. The first method proposes the capture of human position and movement information through motion capture systems along with geometric representations of the human body and robotic manipulators in HRC tasks. The second method relies on contactless devices that provide visual and/or 3D information. These systems are covered in sections IV-C3, IV-C4, IV-C5 IV-C6, IV-C7.

Much work involving motion capture systems focuses on HRC using geometric representations of the environment, and objects within it, which were developed in previous studies before research on human-robot collaboration began. Such early work suggested the use of these geometric representations in collision detection, instead of human-robot collaboration. Examples of the application of geometric representations in robotic environments include [108] and [109]. The former work presents a method for fast collision detection for a manipulator task based on a recursive decomposition of the workspace known as the *Octree Representation Scheme*. The latter work proposes a hierarchical spatial representation based on spheres as a technique for collision detection between an industrial robot and solid objects within its workspace.

Focusing on human-robot collaborative tasks, numerical algorithms have been developed that use a geometric representation of the environment to compute the minimum human-robot distance, and to search for collision free paths. Sphere-based geometric models is a numerical algorithm option used for instance in [106], where predictions of the motions of human and robot are incorporated to minimize the negative effects of a non-instantaneous time response by the robot. To animate the human models, data from a motion capture system are used in the simulations. Simulations involving a PUMA robot arm and a human demonstrated the ability of this method to prevent all collisions between human and robot while the human is walking towards the robot within the robot workspace.

A proposal based on bounding volumes is the Sphere-Swept Lines (SSLs) method presented in [112] and further developed in [113]. This method overcomes the limitations of other models such as the lack of accuracy of systems based on linear skeletons of human and robot; the high computational cost of systems using a mesh of polygons; or the imprecise fitting of spheres to human and robot structures. To localize the human in the robot workspace, the information from a inertial motion capture system is combined with the data from a UWB (Ultra-WideBand) localization system which uses the technique of triangulation of information from four fixed camera sensors located in the workspace and a small tag carried by the human to estimate the human position. The minimum distance between human and robot is calculated in order to identify a risk of impact. When sufficiently high, the value of this risk is used as a trigger to stop the normal trajectory of the robot and to generate an alternative trajectory, with the robot avoiding contact with the human. In [107] this idea was developed further including the use of Axis-Aligned Bounding Boxes (AABB) along the SSLs, Fig. 12, allowing to define a hierarchy of bounding volumes with three levels. This characteristic reduces the number of distance tests to be performed. In addition, this safety strategy was successfully implemented and tested in three assembly and disassembly tasks, guaranteeing human safety in conditions of close proximity between human and robot.



(a)

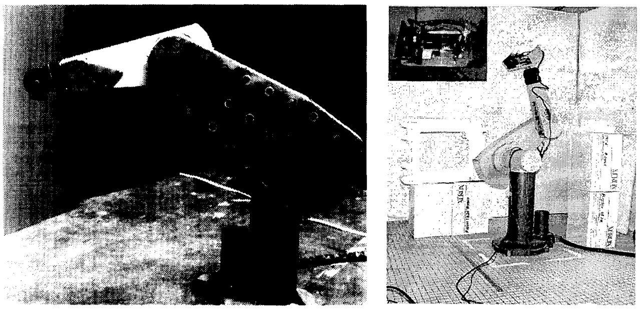
(b)

FIGURE 12. (a) Sphere geometric model of human an robot in [106]. (b) Use of SSLs for an assembly task based on the cooperation of two robotic manipulators and a human operator in [107].

3) SENSORS CAPTURING LOCAL INFORMATION

Early research on avoiding human-robot collisions was focused on acquiring information about the local space surrounding the industrial robot. For this purpose, robot arms were provided with sensors that are able to capture local information. Infra-red proximity sensors [114], capacitive sensors [110], [115], [116], Fig. 13(a), ultrasonic sensors [117], or laser scanner systems [111], Fig. 13(b), have been used as part of collision avoidance systems. However, the information provided by these sensors does not cover the whole scene, and therefore these systems can only provide a limited contribution to improving safety in HRC tasks.

In contrast, their use can enhance the occlusion problems associated with sensors mounted on fixed locations of the workspace as is shown in [100], where 20 distributed Sharp IR-Led sensors were placed on-board of an industrial robot arm. Distance sensors were mounted around the robot arm using the optimisation method proposed in [118], and their signals were used for the calculation of danger field vectors associated to each sensorized link. This information was used as a part of a reactive control strategy that makes the robot perform evasive movements when necessary. The results show that this approach guarantees almost 90% of human detection probability, improving human safety, and at the same time, maintaining task consistency.



(a)

(b)

FIGURE 13. (a) Whole Arm Proximity (WHAP) Sensor Skin on PUMA Robot in [110]. (b) Triangulation based area-scan laser range finder mounted on the PUMA wrist in [111].

4) ARTIFICIAL VISION SYSTEMS

Artificial vision systems have also been used to prevent human-robot collisions. Visual information can be used on its own, or in combination with information from of others types of sensors.

In [120] a safety system for HRC consisting of two modules is described. One module relies on a camera and computer vision techniques consisting of the calculation of the difference of gray level between current image and the reference image to detect changes in the scene, and the use of a shading algorithm [121] to prevent the effects of changes in the illumination. In addition to obtaining the location of the human, this module implements three different robot behaviours, which depend on the measured distance between human and robot. In this way, if no human is in the working area, then the robot works at the maximum programmed speed. However, if a human is detected in the robot working area, but there is a minimum safe distance between robot and human, the robot velocity is limited to a safe value. In case the distance between human and robot becomes too small, the robot is stopped. The other module, which is based on accelerometers located on the robot and on joint position information, is used to prevent an unexpected robot motion due to a failure in the robot hardware or software.

In [119] visual information is used to design a safety system which attempts to deal successfully with several cooperation tasks that are controlled by the robot program (free motion) as well as by the human operator (guided motion), such as transfer motions (gross motion) or assembly tasks (fine motion). To achieve a safe cooperation, the behaviour of the robot is modified according to the distance between the human and an adaptive region of surveillance surrounding the robot arm, Fig. 14. Based on the concept of distance-controlled velocity, the robot decreases its velocity when the surveillance region around the robot approximates a human or object. To achieve the guided motion required in collaborative tasks a force/torque sensor mounted on the robot wrist provides information about the direction of the force and torque that is used to generate the movement of the robot.

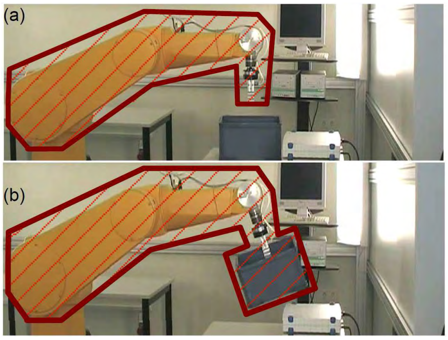


FIGURE 14. **Adaptable area of surveillance on free fine motion [119]. (a) The robot is under surveillance. (b)The entire robot and the object are under surveillance.**

Following the work in [119], the enhanced method presented in [122] includes several fixed cameras to prevent occlusions in images. The captured visual information is given as the input to an algorithm that calculates image differences to detect the position of the human. To differentiate between robot and human, information from the robot position sensors is projected onto the images from each camera, which, together with the estimates of the human position, allows to calculate the distance between human and robot.

Other works have used visual information acquired by static cameras as a means to perform collision tests. These strategies allow to determine whether the space at a requested configuration of the robot is free or occupied by an object. An efficient collision test is presented in [123], where four fixed cameras are used to monitor the workspace. Using image differencing based on binary scene images and several mapping functions to generate the obstacle, intersection, and collision images, a boolean outcome of the collision test is generated.

Occlusions in image sequences from fixed cameras used to detect dynamic obstacles are common and undesirable. According to [124], and based on the work presented in [123], several improvements are made in the object reconstruction in cases involving occlusions. These improvements allow to apply the collision test as a basis for a collision-free path planner. Moreover, a visual approach for image analysis of unknown and known objects was proposed in [125] as an improvement over the earlier collision test methods. An enhanced image differencing method is proposed to obtain the classification of foreground and background pixels. This enables the collision detection for gross motions (transfer or pick and place) and its application to plan collision-free paths for the robot.

In [126] two IP cameras provide information from color marks located on the head and shoulders of the human. This visual information allows to estimate human posture and position in HRC tasks performed in cellular manufacturing. A color filter method, based on the HSV components, was applied to overcome the drawback of different light conditions. 3D information about the center position of each mark was estimated using the *Direct Linear Transformation (DLT)* Method. This vision system was applied in the latter work [101] to a prototype production cell of HRC revealing its effectiveness, Fig. 15.

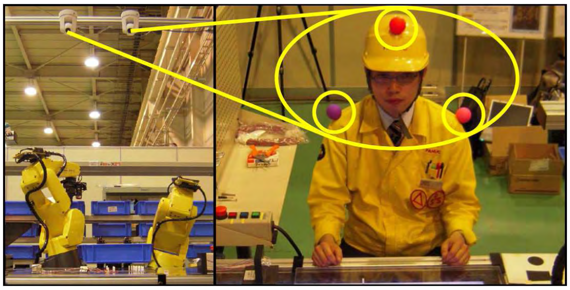


FIGURE 15. **Cameras IP capturing information about color marks [101].**

Artificial intelligence techniques have been used by some authors to develop safety strategies using visual information. To solve the obstacle avoidance problem in [127], safety strategies based on fuzzy logic were proposed. An attracting force towards the goal position, and a repulsive force that represents the distance to an obstacle were defined. To avoid collisions the repulsive force deactivates the attracting force and triggers specific avoidance actions. In [128] the application of the Expectation Maximization (EM) technique to visual information enables to predict in real-time the area where a human is heading and the time when the area is going to be reached.

The commercial safe camera system *SafetyEye* [129], [130] comprises three components: a sensing device that consists of three highly dynamic cameras, which do not need to be calibrated; a high performance computer that operates as the analysis unit and generates a 3D image from the ones captured by the cameras; a programmable safety and control system that controls the whole SafetyEYE operation at works at the same time as the interface to the robot controller. The safe camera system enables uninterrupted three-dimensional monitoring and control of danger zones, detects and reports objects that invade the predefined zones, and decreases the robot speed or stops the movement according to the area that has been occupied by a human.

5) RANGE SYSTEMS

Range systems use light patterns, IR-LEDs, laser, and even stereo camera systems to generate a 3D range map of objects in the environment.

An example of range imaging cameras incorporated in safety systems for robotic industrial environments is given in [131], where the fusion of 3D information obtained from several range imaging cameras and the visual hull technique are used to estimate the presence of obstacles within the area of interest. The configurations of a robot model and its future trajectory along with information on the detected obstacles is used to check for possible collisions.

An extension of the above work is [132] where a general approach is introduced for surveillance of robotic environments using depth images from standard colour cameras or depth cameras. The fusion of data from CCD colour cameras or from ToF cameras is performed to obtain the object hull and its distance with respect to the known geometry of an industrial robot. By means of a experimental setup consisting of several range and colour cameras monitoring the workspace of an robot arm, the authors present a comparison between distance information from colour and ToF cameras, and a comparison between a single ToF camera and ToF information fusion from several cameras. One of the conclusions of this work is that the estimated distance between a robot model and the unknown object using depth information is longer than the distance obtained using information from one colour camera. Another conclusion is that the fusion of information from several ToF cameras provides better resolution and less noise than the information obtained from a single camera.

In [133] two anti-collision strategies are presented and validated on a 1D experimental setup. These methods are based on a virtual force that is computed from information coming from a laser time-of-flight (ToF) sensor, and is used to modify the trajectory of the robot.

In [135] an approach using a soft robot arm along with a depth sensor located at a fixed position of the work cell is discussed and implemented. Their results reveal that a collision could happen when the velocity of a human movement exceeds a threshold related to the depth sensor bandwidth and characteristics. Despite of this, human safety is guaranteed due to the passive compliance system of the soft robot. As a improvement, the authors suggest the inclusion of multiple depth sensors as a means for reducing unmonitored areas caused by the presence of objects in the scene.

An important consideration when attempts are made to avoid a human-robot collision using a combination of multiple sensors is to find the best positioning for the devices, as has been shown in works such as [131]. In [134], to maximize the on-line collision detection performance carried out by the multiple sensor combination, an off-line solution for the optimal placement of depth and presence sensors is presented, Fig. 16. Both sensors are modelled using the pinhole camera model. The presence sensor provides a boolean information in which a pixel is set at *true* in case of detection of an object, and *false* otherwise. The depth sensor generates a depth map that contains the distance between the focal center and a detected object.

In [136] a framework for human-robot cooperation was presented. A key aspect of this work is a scene reconstruction of a robotic environment by markerless kinematic estimation through the use of a range imaging camera mounted at the top of a robotic cell. Background subtraction techniques based on Gaussian Mixture Models were applied. Using background information the decision whether a pixel cluster is generated by a human presence is carried out by means of algorithms based on eigenvalue analysis, depth measurements of pixel distributions, the distribution of connected components and motion features generated from optical flow estimation. This information is employed to extract robust features than model human kinematics, which are the inputs to a fuzzy logic module that estimates risks and controls the robot.

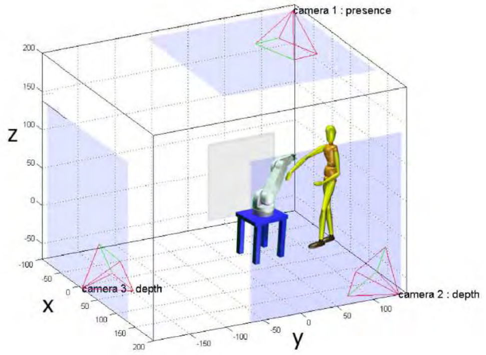


FIGURE 16. A presence sensor and two depth sensors in their optimal placement [134].

6) COMBINATION OF VISION AND RANGE SYSTEMS

This technique relies on the combination of 3D information from range cameras, and 2D information from standard CCD cameras. Although this technique is being used in other applications, such as mixed reality applications [137], or hand following [138] not much work has been reported using it in the area of active safety in robotic environments.

In [140] an analysis of human safety in cooperation with a robot arm is performed. This analysis is based on information acquired by a 3D ToF camera, and a 2D/3D Multicam. This 2D/3D Multicam consists of a monocular hybrid vision system which fuses range data from a PMD ToF sensor, with 2D images from a conventional CMOS grey scale sensor. The proposed method establishes that while the 3D ToF camera monitors the whole area, any motion in the shared zones is analysed using the 2D/3D information from the Multicam.

In [141], a hybrid system based on a ToF camera and a stereo camera pair which is proposed to be applied in HRC tasks is described. Stereo information is used to correct unreliable ToF data points by generating a depth map which is fused with the depth map from the ToF camera. The colour feature is not taken into account. Information fusion involving data captured by both a standard CCD camera and a ToF camera was proposed in [139] as a method to obtain 3D information from a robot cell and to be used in the detection of the proximity between a manipulator robot and a human. This combination of information results in a matrix that links colour and 3D information, giving the possibility of characterising the object by its colour in addition to its 3D localisation, Fig. 17.


(a) (b)

FIGURE 17. **Foreground segmentation in colour images based on foreground detection of 3D points in [139]. (a) Original image. (b) Foreground segmentation in the colour image.**

7) RGB-D DEVICES

Nearly a decade after ToF cameras emerged into the market [142], a new type of 3D sensor known as RGB-D, which is fitted with an RGB camera and a 3D depth sensor, were launched for commercial use [143]. The RGB-D sensor has several advantages over ToF cameras such as higher resolution, lower price, and the availability of depth and colour information. Hence, the study and application of this type of sensor have been the object of research such as [144], which presents a review of Kinect-based computer vision algorithms and applications. Moreover, the work described in [145] proposes an adaptive learning methodology to extract spatio-temporal features, simultaneously fusing the RGB and depth information.

The use of the Kinect sensor can be an alternative to standard vision cameras or to range systems in collaborative robotics. For example, in [104] the depth sensor of the Kinect is modelled as a classic pin-hole camera to capture the depth space of the environment. To achieve real-time collision avoidance, the robot-obstacle distance was estimated and used to modify on-line the trajectory of the robot arm, Fig. 18. In later work, an improved approach to evaluate the distance between a point of interest in the Cartesian space and the objects detected by the RGB-D sensor was presented and tested in a highly dynamical human-robot collision avoidance task [146].

FIGURE 18. **Avoidance of human-robot collision using RGB-D information [104].**

In [147] the use of an RGB-D camera is focused on the achievement of safe collaborative tasks on an assembly line. For this purpose the camera was placed above de operator to reduce occlusions. Based on depth information a learning and recognition procedure was used to recognize gestures of the human hands. Gesture recognition can be a valuable help in collaborative tasks, as it can be used to prevent collisions when unexpected events occur by detecting which task has just been completed by a human, thus enabling the robot to anticipate the human's actions, and then adapt its speed and react in a suitable manner. Other examples are given in [148] and [149], where the motion of the robot is derived from the perceived arm movements of the human, thus allowing the human to guide by example the robot in performing manipulation tasks.

V. DISCUSSION

This review provides an insight on the evolution of safety systems and their application in robotic environments, allowing collaborative human-robot work, including tasks involving interaction tasks. Owing to the shifts in human-robot relationship which are reflected in the international standards aimed at industrial robotic environments the changes in relevant standards have been discussed, which has involved the inclusion of new definitions and the consideration of new risks. To illustrate the types of safety systems under consideration, a matrix was designed to associate at a glance the aims of different safety systems, software, hardware systems and devices employed, and the robot behaviour in each case. A description of each safety aim and the corresponding systems and devices has been presented. The inclusion of cyber-physical-systems in this matrix provides a connecting link between different systems geared to achieve the sharing of workspaces between human and robots. The use of the CPS approach in human-robot collaboration has been discussed, highlighting current technological limits and challenges associated with the real-time implementation of this approach in human-robot collaboration.

The knowledge and quantification of human limits in terms of level of pain and injury, through simulated or controlled human-robot impacts, has contributed achieving active safety in industrial robotic environments. With regard to quantifying the level of injury by collision two different points of view have been discussed. The first one provides estimations of the level of pain that a human can tolerate, while in the second approach, several indices that have been used by the automotive industry have been discussed. Although such indices are not perfectly suitable in the context of industrial robots, however, they have been useful to evaluate new safety systems. It should be pointed out that with the recent standard ISO-TS 105066:2016 a suitable procedure to stablish speed limits for the robot to avoid major injuries to a human in case of human-robot collision is now available.

Since collision avoidance cannot always be guaranteed in human-robot collaboration, different mechanical systems and safety strategies for collision detection have been described which minimize injury in case of human-robot collision. The reviewed literature shows that several of these mechanical systems have been tested using numerical models or actual experiments, and their benefits have been quantified by means of the most suitable injury indices. The reviewed results show that viscoelastic covering seems to be adequate to absorb impact energy. However, this covering in combination with absorption elastic systems have produced clearly improved results. These ideas have been implemented in commercial light robots that seek to enable safe collaborative human-robot work. Moreover, software developments have been proposed and tested in combination with mechanical compliance systems as a method that not only helps to minimize injuries, but also allows for intentional human-robot contact in human-robot interaction, opening a wide field of research.

Although mitigating the consequences of human-robot collisions is vital, the prevention of unintentional contact is most advisable. As a consequence, various safety systems focusing on collision prevention have been proposed. Various pre-collision strategies have been presented in this paper. Their main characteristic is that, based on information about the robot motion and configuration, together with information about the human that is obtained from vision systems and other sensing modules, an alternative path for the manipulator robot is computed, moving the robot away from the danger zone when a collision is predicted.

A way to collect information about unknown or uncertain parts of the environment is using motion capture systems and simulated environments. Using this information, geometric representations of human and robots are generated. These representations are usually based on bounding volumes. By using this simulated representation, the distance between human and robot can be estimated and incorporated into pre-collision strategies. When a risk of impact is identified, a safety protocol is activated to generate alternative trajectories and move the industrial robot away from the human.

A different way of acquiring information about the surroundings of the robot relies on contactless devices such as sensors that capture local information or devices that allow capturing global information from the work area. Infra-red proximity sensors, capacitive sensors, ultrasonic sensors, or laser scanner systems, belong to the first type of contacless devices and were used in some of the early works in this area. However, constraints associated with capturing information about the environment surrounding the robot make these approaches not suitable by themselves. Yet, some researchers have found ways of avoiding occlusion problems associated to sensors located on fixed placements through the use of this type of devices.

Although the use of motion capture systems along with simulated environments has produced good results in the implementations that have been reported (and to overcome the limitations of local sensors), fixed devices monitoring the work area seems to be a feasible alternative to the these acquisition systems. Using standard cameras and range systems, there is no need to place markers on the human body. Moreover, they can give information about any unexpected object that may enter the working area. The section on artificial vision systems of this review paper discusses methods that have been proposed to prevent robot-human impacts using standard cameras and computer vision techniques.

Finally, a review of recent research based on devices that provide 3D information which is used to achieve safety in robotic environments is also provided. The emergence of devices such as ToF/PMD cameras, or RGB-D devices, has resulted in a reduction of the efforts to extract 3D information from the scene. Combining 3D information along with colour information has been proposed as a way of extracting more comprehensive information about the area of interest. Several algorithms for the fusion of 3D and 2D information have been discussed. However, the technology is progressing and devices that fuse automatically these kinds of information have emerged. Although these devices were not originally intended to be used in robotic industrial environments, some research point to this possibility, as reflected in the discussion on RGB-D devices.

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