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Safe physical human robot interaction–past, present and future

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Abstract

When a robot physically interacts with a human user, the requirements should be drastically changed. The most important requirement is the safety of the human user in the sense that robot should not harm the human in any situation. During the last few years, research has been focused on various aspects of safe physical human robot interaction. This paper provides a review of the work on safe physical interaction of robotic systems sharing their workspace with human users (especially elderly people). Three distinct areas of research are identified: *interaction safety assessment, interaction safety through design, and interaction safety through planning and control*. The paper then highlights the current challenges and available technologies and points out future research directions for realization of a safe and dependable robotic system for human users.

Keywords: Human robot interaction; Service robot; Safety

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1. Introduction

Robotics technology research is shifting its focus from industrial applications to human-centered applications. The ultimate goal is to reduce fatigue, augment the power and improve the quality of daily life of all humans in general and elderly people in particular. Surveys show that elderly people want to live independently and are more interested in robotics technology for their daily life tasks [1-3]. Many robotic systems with varying characteristics and capabilities are proposed to serve the purpose. They range from small entertainment robots [4] to mobile manipulators equipped with conventional robotic arms [5]. Classification of such robots can be made on the basis of application modes. Typical application modes include *cooperation, assistance, teleoperation and entertainment*, etc. In cooperation mode either the robot is physically guided by a human operator during a task [6-9] or the human and robot working together on the same physical task cooperatively to use the power of the robotic system and intelligence of a human user to carry out the physical task [10] as shown in Fig. 1. In assistance mode, physical interaction may be either for short duration (as in assisting in daily life tasks) or the robot is physically connected to the person's body for a comparatively long time such as a power extender [11-12], physical training/exercise, and supporting a human etc. Fig. 2 shows the concept of power extender, and Fig. 3 shows the concept of physically supporting a human for walking and exercises. In teleoperation, a person normally interacts with a small master robot, whereas entertainment robots (like Sony's Aibo etc.) are generally smaller in size. The latter two types may be regarded as safe because either they do not physically interact with human(s) or they do not pose any serious threat due to their small size, while the former two types closely interact with the human(s) and may be dangerous.

Note that generally the term 'human robot interaction' is used for *physical* as well as *cognitive* interaction. However, this paper is focused on *physical*

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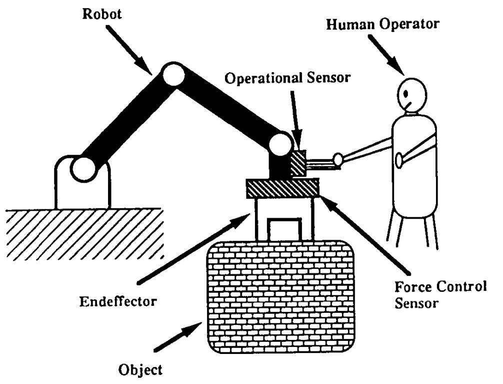


Fig. 1. Concept of human-robot cooperation (reproduced from [6] © (1991) IEEE).

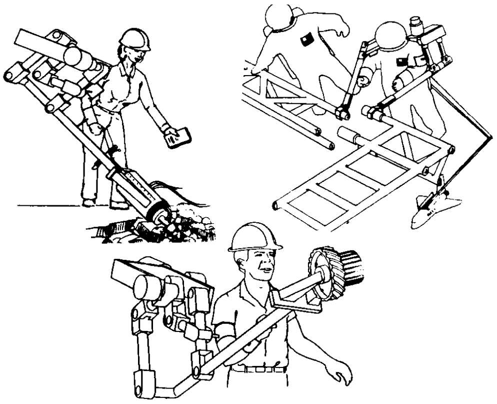
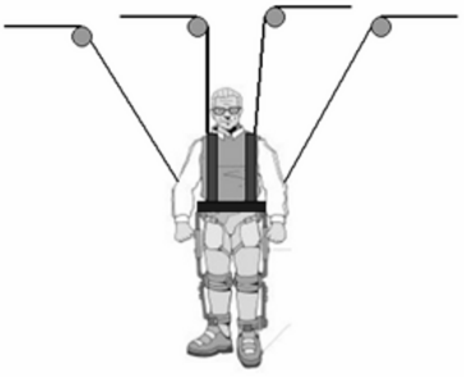


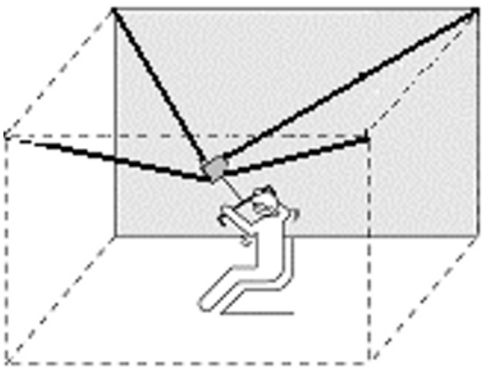
Fig. 2. Concept of power extender (reproduced from [11] © (1989) IEEE).

human robot interaction (pHRI) [13] and does not consider the *cognitive human robot interaction* (cHRI) [14]. The former includes all types of physical interactions described earlier; the latter is mainly concerned with perception, awareness and mental model. More on cognitive robotics can be found in [15, 16]. Hereinafter the word 'interaction' is used for physical interaction of robots with human users.

Physical interaction of robots with human(s) poses new requirements for robotic systems to fulfill. The most critical requirement is to guarantee the safety for non-professional persons who are either using the robot or are present around the robot. For applications involving close interaction with robotic systems, the previous concept of safety based on the principle of not allowing any person to enter in the workspace is no longer useful. However, without concrete safety guarantees, robots cannot be allowed to work in close proximity to humans.



(a) Posture balancing

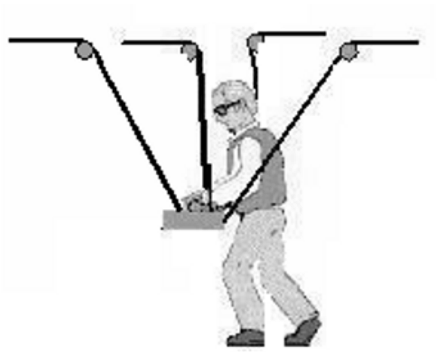


(b) Muscle strengthening.

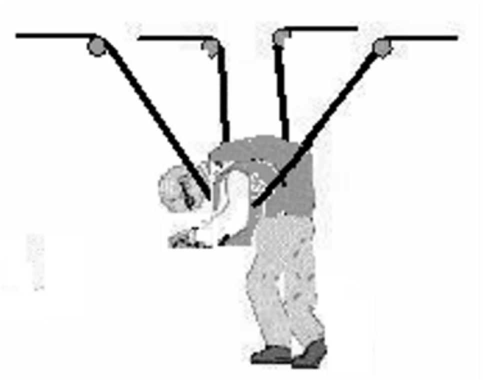
Fig. 3. Rehabiliataion exercises.

Classification of physical interaction can also be made on the basis of environment type, i.e., *active* or *passive*. If an environment/human transfers energy to the robot during interaction, it is termed as active; otherwise, it is termed as passive. A typical example of active (passive) interaction is active (passive) walking. In *active* walking, the user walks on the ground while the robot supports his/her body weight and the ground reaction forces act on the robot system. In *passive* walking, the user is lifted and transported by the robot similar to a load towards a predefined destination, and thus no ground reaction forces are generated. A conceptual view of active walking and passive walking is shown in Fig. 4 (a) and (b), respectively.

The physical human robot interaction, should it be planned or accidental (i.e., collision), must be safe for humans as well as the robot itself. The collision of a robot with a human is a major source of injury in such applications. A large amount of research work is available for collision detection and avoidance.



(a) Active walking



(b) Passive walking.

Fig. 4. Walking modes.

However, collision avoidance cannot be guaranteed hundred percent [17], so other methods for safety guarantee are inevitable. Researchers have worked on different aspects of physical human robot interaction and presented certain important findings and solutions. This paper reviews the research work in the area of physical human robot interaction and points out certain new research directions for achieving a safe and dependable physical human robot interaction. A periodic review of research work is very important to assess it in terms of achieving the targets and/or redefining the research directions, if otherwise. Note that this work is different from that of Yanco and Drury [18], which considers human robot interaction in terms of intervention/guidance in the robot's operation. Moreover, the safety and dependability issues were not discussed in that paper. This paper is also different from [19] in the sense that latter is more focused on actuator design and dependability issues and does not mention the work on robot danger formulation for human-robot symbiosis and safe interaction control.

A closer look at research work in physical human robot interaction shows three distinct areas: quantitative description of safety concept, achieving safety through design, and (or) through control. These will be considered and analyzed thoroughly in subsequent sections.

This paper is organized as follows: Section 2 reviews the related work in safe physical human robot interaction highlighting three distinct directions. The present challenges and available technologies are considered in section 3, whereas section 4 discusses possible future research directions. Section 5 concludes the paper.

2. Review of previous work

The sharing of a robot's workspace without any harm to humans (and to robot itself) has been the goal of research in the domain of physical human robot interaction. The work was carried out on different fronts which can be described under three headings:

(A) Interaction safety assessment,
(B) Interaction safety through design, and
(C) Interaction safety through planning & control.

In the following, each category is described briefly.

2.1 Interaction safety assessment

The concept of 'safety' is vague and is described qualitatively which is not useful for evaluating the strategies to achieve a it. Therefore, a quantitative description of safety concept is very important for the safety guarantees. For this reason, efforts are focused on defining safety in quantitative terms. Different indices, primarily borrowed from automotive industry crash tests, were used to evaluate the risks to human safety. Among them, *Gadd Severity Index* (*GSI*) [20] and *Head Injury Criterion* (*HIC*) [21] are the most common. They are defined as below:

$$GSI = \int_0^t a^{2.5} d\tau \tag{1}$$

$$HIC = T\left[\frac{1}{T}\int_0^T a(\tau)\, d\tau\right]^{2.5} \tag{2}$$

where a is the head acceleration in terms of g, T is the final time of impact, and t is the whole duration of collision. Values of *HIC* and *GSI* greater than 1000 are considered as associated with severe injury. A discussion of some other common injury indices can be found in [22].

Heinzmann and Zelinsky [23] considered the *safe impact potential* as a safety guarantee for physical human-robot interaction. A safe impact potential refers to the condition that the maximum impact force that a moving mechanical system can create in a collision with a static obstacle is within safe limits. Impact force, $\hat{\boldsymbol{F}}_I$ at a particular point p on the surface P for a serial robot manipulator, is given by [24]:

$$\hat{\boldsymbol{F}}_I = -\frac{(1+e)\boldsymbol{v}^T\boldsymbol{n}}{\boldsymbol{n}^T\boldsymbol{Q}\boldsymbol{n}} \tag{3}$$

with $\boldsymbol{Q} = \boldsymbol{J}(\theta)\boldsymbol{I}^{-1}(\theta)\boldsymbol{J}^T(\theta)$; $\boldsymbol{n}$ is the normal vector of contact plane, $\boldsymbol{I}$ is the $n\ x\ n$ inertia matrix, and $\boldsymbol{v}$ is the velocity at point p. The constant e denotes the type of collision; it is zero for purely plastic collision and unity for purely elastic collision. Eq. (3) shows a clear dependence of impact force on velocity, inertia matrix and contact geometry. The impact potential, ς , is then defined as [23]:

$$\varsigma = sup\, \varsigma_p \tag{4}$$

where, $\varsigma_\mathrm{p} = \hat{F}_I$ at point p of surface P and *sup* stands for supremum.

Ikuta et al. [25] presented the first-ever quantitative generalized danger index and described the basic factors affecting the safety of humans sharing a robot's workspace. Danger index, *DI,* is defined as the ratio of maximum producible impact force $\hat{F}_I$ to safe critical force F_S , given by Eq. (5) as [25]:

$$DI = \frac{\hat{F}_I}{F_S} \tag{5}$$

The overall danger index was computed as the product of different danger indices, including the danger indices of design strategies like reducing weight, elastic covering, and joint compliance etc., and danger indices of control strategies, like keeping a safe distance between user and robot, reducing approach velocity, posture with minimum inertia and minimum stiffness etc. This work, however, did not address the implementation of danger index for real time control of robotic system.

Kulic and Croft [26] adopted the same concept of *danger index* (DI) as the product of different danger factors of control strategies. But they used empirical formulae for deriving each danger factor. The danger index, *DI*, was formulated as "product of distance factor, f_D , velocity factor, f_V , and inertia factor f_I " [26]:

$$DI = f_D f_V f_I \tag{6}$$

where f_D , f_V , and f_I are defined in [26].

Oberer et al. [27] highlighted the need to further clarify the quantifiable scoring by combining the knowledge of potential human injury with the work of Ikuta et al. [25]. They pointed out that different body regions have different severity score, according to AIS-90, Abbreviated Injury Scale-Revision 90, scaling of injuries [28]. Thus, a knowledge of the severity of possible injuries is very important to assess the actual risk from a robot during human-robot interaction.

2.2 Interaction safety through design

The second category of research work in safe physical human robot interaction belongs to the new mechanical designs of robotic systems that are less harmful to the humans present in their workspace. Such robotic systems are achieved through (1) design of lightweight manipulators, (2) design of passive compliant systems, (3) design of safe actuators, and (4) design of passive robotic systems, etc.

2.2.1 Design of light weight manipulators

Lightweight structures assure a better safety performance, in case of collision, due to modern lightweight materials in axes and links. However, they lack the power to replace the classical serial robots in many applications. Examples of such systems are the whole arm manipulator (WAM) [29] and DLR lightweight arm [30] etc.

2.2.2 Design of passive compliant systems

The design of viscoelastic material-covered robot manipulators [31], compliant trunk with passive movable base [32], and cable-driven manipulators such as Dexter [33], SpiderBot-II [34] etc., are typical representatives of this class. Dexter is an anthropomorphic 8 degrees of freedom cable-actuated robotic arm designed for human user. SpiderBot-II is an incompletely restrained wire-driven parallel mechanism intended to be used for walking and manipulation assistance of elderly and handicapped persons in the home environment. The concept and application scenarios for SpiderBot-II can be found in [35]. SpiderBot-II consists of an end-effector suspended by four wires passing through pulleys fixed at four corners of room at a suitable height. This structure is inherently safe, economical, and easy to install inside the home environment without any significant structural modification. A safety analysis of SpiderBot-II is reported in [34]. Due to being an incompletely restrained system, its end-effector may experience oscillation which can be reduced either by increasing weight at the end-effector or employing an anti-sway controller [36].

Cable-driven manipulators are generally considered inherently safe as they do not produce the large impact load associated with high-impedance design. However, due to low resonant frequency of many cable–driven manipulators, high performance control of such systems is difficult, if not impossible [17]

2.2.3 Design of safe actuators

To achieve the safety as well as motion control performance, efforts are carried out to design new types of actuators. These include joints based on programmable passive impedance [37], mechanical impedance adjuster [38], joint torque controlled actuation [39], series elastic actuators (SEA) [40], variable stiffness actuators (VSA) [41] and distributed macro-mini (DM^2) [17, 42].

For achieving programmable passive impedance [37], a non-back-drivable actuator, emphasized by a worm gear, drives the link through a transmission with programmable stiffness and viscous damping coefficients. A mechanical impedance adjuster [38] consists of a mechanical compliance adjuster composed of a spring unit, a pseudo-damper by brakes and a joint-driving unit. The implementation of joint torque control [39] allows for near-zero low frequency impedance, which gives excellent force control characteristics. However, it is not very effective in reducing impact loads mainly determined by impedance of contacting surfaces at frequencies above the control bandwidth [17].

Series Elastic Actuators (SEA) [40] use a passive mechanical spring in series with a gear that acts as a low-pass filter for shock loads and thus reduces high gear forces. However, this arrangement is not suitable for high bandwidth tasks like high frequency disturbance rejections etc. [17]. Variable stiffness actuators [41] are designed solely for tasks involving interaction with humans and are based on the *variable stiffness transmission* (VST) principle. Each actuator consists of two motors and spring arrangement and allows control over displacement as well as joint stiffness. A preliminary design is described in [43]. The possibility to vary transmission stiffness (or impedance, in general) is a useful way to guarantee low levels of injury risks during execution of fast trajectory tracking tasks. Variable stiffness transmission approach is suggested for gain in performance and guaranteeing safe joint actuation. Performance of VST is dependent on range of compliance variation at the joint. However, the control of VST-based robotic arms is more complex due to continuous variation of joint stiffness [17]. Bicchi et al. [22] suggested some possible solutions to this problem.

DM^2 [17, 42] approach is similar to Parallel Micro-Macro concept proposed by Morrell and Salisbury [44]. It consists of a low frequency base actuation and a high frequency joint actuation. Thus, torque generation is distributed into low- and high-frequency components for base load and disturbance rejection respectively. The fundamental condition for DM^2 approach to work is that each actuator must not have significant impedance within frequency range of the opposing actuator [17].

The other notable solutions based on approach of variable compliance actuation include frictionless pneumatic actuators [45], magneto-rheological fluid based actuators [46, 47], and smart flexible joints [48]. However, VST, SEA and DM^2 seem to be more useful schemes because they are relatively easier from control point of view as compared to other schemes. A comparison of VST, SEA and DM^2 schemes can be seen in [49]. Some interesting robotic applications of variable compliance actuators such as bipedal robotics and rehabilitation assistive devices are described by Verrelst et al. [50].

2.2.4 Design of passive robotic systems

A very important approach towards safe physical systems is to develop passive robotic systems [51]. Typical examples of such a system include RT Walker [52] and Cobot ([9]. RT Walker uses servo brakes instead of servomotors and by using relative brake forces in rear wheels it can maneuver and avoid obstacles and other dangerous situations. More on passive robotics is discussed in [53]. Cobots are a class of inherently passive robots intended for direct collaborative work with a human operator. Their main contribution is to bring a *virtual* environment, defined in software, into physical effect on the motion of a *real* payload. They implement virtual surfaces by using *continuously variable transmissions* (CVT) that consist of two drive rollers, two follower rollers and two steering rollers. The velocities of two drive rollers are coupled through steering roller angle Φ. CVTs are connected either in serial or in parallel fashion. Note that in both serial and parallel structures, the number of mechanical constraints imposed by the CVT transmission ratios lowers the number of degrees of freedom to one. Another classification of CVTs is based on the nature of velocity they are coupling. *Translational* CVT constrains a pair of linear speeds while *rotational* CVT relates two angular velocities. Although Cobots belong to the passive robotics class and do not have any actuator other than steering, a new class named as *Powered Cobots* uses a single power actuator but with power less than that of a human user. This limitation of power makes them safer for humans.

2.3 Interaction safety through planning & control

Interaction control with a known passive environment was addressed in last few years and two main categories of impedance control emerged: *statically compensated* and *dynamically compensated*. The former class includes techniques like stiffness control, force control and parallel force/position control, whereas the latter contains techniques like classical impedance control [54-56], impedance control with inner position loop, force control with inner velocity loop, force control with inner position, and hybrid force position control [57,58]. A survey of interaction control schemes with known passive environment is provided by Chiaverini et al. [59] and Natale [60].

The impact force is considered as the major cause of injuries during unplanned interaction with humans; thus, methods to reduce the impact force are needed to enhance safety guarantee. Use of protective covering is one possibility, but using it alone to absorb the impact force may not be effective as discussed in [17]. Similarly, design techniques also have compliance limits; thus, safe interaction through planning and control becomes very important. Two classes can be identified for this category and are described below.

2.3.1 Interaction safety through planning

This category is mainly focused on navigation and collision avoidance in an environment shared by human and robot. Interaction control through planning has been investigated by many researchers [26, 61-63, 23]. Kulic and Croft [26] proposed the use of the danger index in Eq. (6) as input for real-time trajectory generation when the index exceeds a pre-defined threshold. The danger index is used to generate a repulsive force similar to artificial potential force proposed by Khatib [64] and move the robot to a safer place in case of danger. The human was considered an obstacle and maximum effort was devoted to avoid it or to stop the robot if there is no way to avoid. The danger index was based on distance and velocity factors originally proposed by Ikuta et al. [25]. In another work [61], Kulic and Croft established a cost function consisting of the sum of goal seeking criterion, obstacle avoidance criterion, and danger criterion. The planned path was generated by searching for a set of configurations that minimized the cost function. Liu et al. [62] proposed an interaction strategy with six kinds of planning actions to keep a safe distance and predict collisions in dynamic environment. The main contribution claimed in this paper is the rapid mapping of a moving obstacle into invalid and dangerous edges in the roadmap.

Heinzmann and Zelinsky [23] proposed an impact potential control scheme that checks the nominal torque generated by trajectory generator for a safety envelope. As described earlier, the impact potential is the maximum impact force that a moving mechanical system can create in a collision with a static obstacle. The impact potential control scheme checks the nominal torque generated by trajectory generator for the safety envelope and clips it if it is outside that envelope. Wosch et al. [63] considered the man-machine interaction scenario in dynamic environments with moderate complexity and proposed an integrated control architecture combining planning and reactive components. They presented a motion planner interacting with reactive plan execution system to avoid obstacles. Task oriented motions are executed according to reactive plans biased by a target configuration. Approach was implemented on an eight DOF mobile manipulator.

2.3.2 Interaction safety through control

This sub-section describes the efforts for achieving interaction safety through control. The idea is to control the stiffness/compliance to reduce the impact force during collisions. Zollo et al. proposed interaction control schemes based on exponential position and force error [65] and coactivation function [66]. In the former work, compliance control in Cartesian space, compliance control in joint space, and impedance-compliance control schemes were investigated. The position error was considered as an indication of a collision and was used to control the compliance of the system. In the latter work, a coactivation function inspired by biomechanics and based on position and force error was used for interaction control. Formica et al. [67] suggested the use of measured torque to vary the compliance for motor therapy exercises and thus achieving safe interaction control. Note that these schemes are variations of statically compensated impedance control techniques described earlier.

Lim and Tanie [32] proposed a collision-tolerant control scheme for a robotic system composed of a viscoelastic trunk and a movable base. In this work, the collision effects are absorbed by viscoelastic trunk and movable base and collision-tolerant control takes care of motion inaccuracies due to collision. A similar approach was adopted by Li et al. [68] for a mobile manipulator working in human robot symbiotic environments. Recently, Park and Khatib [69] presented a compliant motion control framework for multiple contacts distributed over multiple links. Note that these strategies are more concerned with task accuracy rather than impact force reduction during a collision. Table 1 shows a summary of research issues and their solutions by various researchers and relevant references.

3. Challenges and technologies

The grand challenge for the robotics community is to develop systems with high degree of safety and performance for human-centered robotic applications. Such robotic systems are now termed as ‘safe and dependable’ in the literature [19, 70]. Safety includes the design of lightweight mechanisms, failure management, and safe physical interaction control, as discussed in section 2. The high reliability and availability make a robotic system dependable [19]. To meet the challenge, expertise in various technologies like mechanical design, sensors, control, intelligent systems design and software is required.

In the following, we shall describe the present available technologies that can be used for guaranteeing safety and dependability. As described earlier, collision with humans is the major threat of human injury. To avoid collisions, obstacle avoidance [71, 72] is an essential requirement of such systems. However, to achieve 100 percent collision avoidance guarantee is still a challenge. Collision-avoidance techniques deal with pre-collision safety and do not focus on reducing the major cause of injury, impact force. The reaction behavior after a collision is a useful feature to reduce the impact force. However, early detection of collisions is needed [73, 74]. Recently, Frigola et al. [75] presented the use of sensitive bumper skin for early collision detection as well as the contact point.

The most natural and useful technologies are vision and force control. The advances in robot vision are proving it a feasible sensor for robotic systems. The use of vision sensor for object manipulation in domestic environment applications is reported by Kragic et al. [76]. Different combinations of sensors are also reported, including integration of vision and force sensor [13, 77] vision, force and joint sensors [78], and force and acceleration sensors [79] that can be used to achieve safety and performance in human robot symbiosis.

Three different configurations of visual sensors are used by researchers: eye-in-hand, eye-to-hand and hybrid eye-in-hand/eye-to-hand [13]. Lippiello et al. [78] used vision for pose estimation of end-effector while in free space and for estimation of the geometry of the environment, though augmented by joint position sensors, while interacting with the environment. Quite recently, Kroger et al. [79] reported the fusion of force and acceleration measurements for compliant motion control. Generally, the robotic arms are position-controlled systems equipped with joint encoders for feedback. However, due to the importance of force control for interaction with the environment, force sensors are being integrated with new robotic arms [80].

The level of autonomy in human-centered robots is another issue of vital importance. Yu et al. [81] reported that elderly people do not like fully autonomous robotic systems and they proposed an adaptive shared control scheme which is based on the user’s physical conditions at the moment. A shared control strategy is normally applied because the user may not be fully stable and therefore full manual control is not allowed. How to share the control between user and computer to ensure safety as well as the user’s au-

Table 1. Summary of research issues and relevant references in safe human-robot interaction.

S. No.	Category	Method/Issue	References
1.	Interaction safety assessment	Injury indices (Discussion)	[22]
		Impact potential	[23]
		Impact force formula	[24]
		Danger index formulation	[25]
		Empirical formulae for danger index	[26]
		Severity of injury	[27]
		Scaling of injury severity	[28]
2.	Interaction safety through design	Whole arm manipulator (WAM)	[29]
		Light weight arm	[30]
		Visco-elastic material covered manipulator	[31]
		Compliant trunk with passive movable base	[32]
		Dexter (Wire driven serial arm)	[33]
		SpiderBot-II (Wire-driven parallel mechanism for assisting elderly)	[34, 35]
		Programmable passive impedance	[37]
		Mechanical impedance adjuster	[38]
		Joint torque controlled actuation	[39]
		Series elastic actuators (SEA)	[40]
		Variable stiffness actuators (VSA)	[41]
		Distributed macro-mini (DM^2) actuation	[17, 42]
		Frictionless pneumatic actuators	[45]
		Rheological fluid based actuators	[46, 47]
		Smart flexible joints	[48]
		Passive Robots	[51]
		RT-walker (Servo brakes based walking assistance system)	[52]
		Cobots	[9]
3.	Interaction safety through planning and control	Trajectory modification on danger index	[26]
		Impact potential control	[23]
		Combined planning and reaction	[63]
		Cost function based on danger, goal seeking criteria and obstacle avoidance criteria	[61]
		Interaction control based on exponential position and force error	[65]
		Co-activation function	[66]
		Measured torque based control	[67]
		Collision tolerant control	[32]
		Impedance control	[54-56]
		Hybrid position /force control	[57, 58]

thority is one important research issue for service robots. Moreover, with fully autonomous systems, the responsibility of accidents cannot be attributed correctly. Laschi et al. [82] proposed adjustable autonomy for human-centered robots. The basic idea is that of setting up a discrete scale of autonomy levels, which enables the user to access robots with different levels of involvement. Fig. 5 shows the different levels of autonomy, from total autonomy of the user to total autonomy of the system. The level of autonomy for robots involved in physical human robot interaction is still a research issue for human-centered robotic systems.

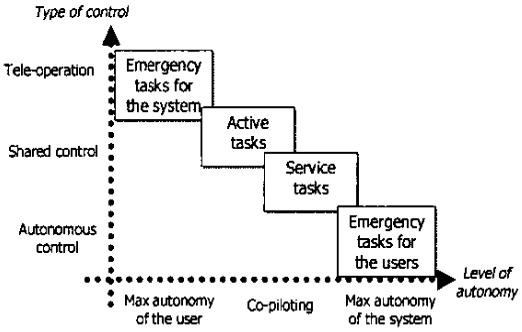


Fig. 5. Levels of autonomy (reproduced from [82] © (2001) IEEE).

In the view of unavoidable collisions, it appears mandatory to have some kind of operation recovery scheme to complete the tasks afterward which were disturbed due to collision. Kosuge and Morinaga [83] proposed such a system which is composed of dynamic collision detection system and operation recovery scheme. The robot stops its motion by the collision detection system when a collision occurs and restarts its motion by operation recovery scheme when the cause of the collision is removed. Similarly, a collision-tolerant control scheme by Lim and Tanie [32] is another example of operation recovery scheme.

4. Future research directions

Previous sections have highlighted the earlier work and challenges regarding two basic requirements for human-centered robots: safety and dependability. This section will point out some possible research directions. Note that safety also includes the proper failure management of mechanical hardware, actuators, software, sensors, and control. Any control system, however robust it may be, cannot be guaranteed against failures. Likewise, software integrity is also a point of concern. We suggest a multi-level safety scheme comprised of (1) *control system* and (2) *protection system* for human-centered robotic assistants. A control system consists of computation of danger potential function, comfort level and a motion control algorithm for safe interaction control. The level of human intelligence usage for guidance and critical decisions is the responsibility of the control system. The protection system is to observe, in addition to danger, a set of critical variables relating to the condition of mechanical hardware, software, sensors and controller, etc. Whenever there is any abnormal behavior which cannot be coped with by the control system, the protection system must take control to move the system to a safe configuration and safely shutdown the system. However, a safe configuration may be different for different application scenarios and needs to be decided after a detailed analysis. The design of such protection system and selection of critical variables/parameters is one future research direction.

Dependability is a vast area that may include many aspects like the performance metrics for servo systems (e.g., response time, settling time, overshoot, and stability), reliability, and availability. It is important to define the concepts of safety, reliability and availability in more robust and quantitative terms to apply for robotic system evaluation. The reliability of an operating system and control software is an important step for ensuring safety and dependability. The fault tree analysis technique [84] is a typical example to ensure the safety critical software's reliability. However, more robust techniques are required for this purpose because the fault tree analysis techniques can only increase the confidence level but there are no techniques to guarantee software safety in terms of non-occurrence of undesired events, i.e., failure of critical software.

Danger [25] is one promising concept associated with pre-collision safety. For estimating danger, detection of human(s) in the robot workspace is very important. Different techniques are proposed for this purpose, including vision system [26] and PIR sensors with camera [85] etc. For sensing danger, a knowledge of human activities and behavior is also very important [86, 87]. We suggest that reliability of safety critical sensors must be enhanced through diversity and redundancy. Similarly, more robust and dedicated sensors are required for danger sensing.

When a human enters the workspace of a robotic system, the environment is neither passive nor completely known any more. Thus, for a partially known *active* environment (an environment capable of transferring energy to robots such as active walking mode, described earlier, is termed here as active environment), the available interaction strategies, originally developed for known passive environment, need to be modified accordingly. This situation necessitates the sensing of his/her intent to modify the nominal trajectory accordingly. Work on intention sensing is reported by many researchers including Colgate et al. [88], Noguchi et al. [89], and Wasson et al. [90]. Another possibility is to install sensors in the environment to make the space around the robot intelligent. Nakauchi et al. [91] developed a vivid room to detect human intentions and monitor human activities. Human behaviors are detected through many kinds of sensors at doors/drawers, micro-switches at chairs, ID tags on humans, and that information is collected by sensor server via RF-tag system and LAN. In order to recognize human intentions (i.e., studying, eating, resting, etc.), a learning system is employed.

However, having too many sensors requires a high computational load and long processing time. To reduce the delays caused by computations and processing, an *expected perception* (EP) scheme [92] can be used by exploiting the fact that the home environment is partially known. The distribution of sensors between the environment and the robot itself is application dependent. For indoor applications, it is always useful to install some sensors in the environment to make it intelligent. However, optimal distribution of sensors between robot and environment is an open question.

In general, a trade-off is essential between safety and motion control performance. In optimal control theory, this problem is called the *safe brachistochrone* problem. The problem formulation and results for a VIA (variable impedance actuator) are reported by Tonietti et al. [93]. Essentially, all the safe interaction strategies, should they be design or control, are exploiting compliance for this purpose. However, too much compliance in a controller can result into stability problems, while compliance in design is limited to a certain value and it is not easy to modify it beyond that limit. Therefore, some suitable hybrid active/passive interaction control schemes [94] can be investigated, taking into account the merits and demerits of each scheme.

Besides safety and dependability, some other capabilities are also needed for successful introduction of robots for human users. These include integrated mobility and manipulation, cooperative skills between multiple robots, interaction ability with humans, efficient techniques for real-time modification of collision-free path [95] and efficient grasping [96]. The other important characteristics of robotic manipulators, specifically developed for humans, in addition to technical requirements, are low-cost, simple installation and ease of use. The key to a widespread acceptability of any product among consumers, besides its performance, is a suitable price. This dictates that such robotic systems must not use too much intelligence and sophisticated sensor systems as they will make the price even higher. Human intelligence is always available for such systems and must be used for critical decisions. This will also address the responsibility issue in case of accidents.

5. Conclusion

A review of safe physical interaction schemes is presented in the context of human presence in the robot workspace. The future of service robots depends on safety, performance, price, simple installation and ease of use. As much as they are guaranteed, the demand for service robots would increase. Should it not be fulfilled, they will remain just inside the labs. One important feature of this work is the identification of future research directions. These include design of multi-level protection strategy, failure management, enhancement of safety through diversity and redundancy of sensors, modification of interaction control scheme, and application of optimal control theory for *safe brachistochrone* problem.

Nomenclature

a : Head acceleration, in terms of g
DI : Danger Index
e : Coefficient of restitution
$\hat{F}_I$: Impact force
F_s : Safe critical force
g : Gravitational acceleration, 9.8 m/s^2
$\boldsymbol{I}$: $n \times n$ inertia matrix
$\boldsymbol{J}$: Jacobian matrix
$\boldsymbol{n}$: Normal vector of contact plane
T : Final time of impact
t : Duration of collision.
$\boldsymbol{v}$: Velocity
θ : Joint angles
ζ : Impact potential

Subscript

I : Impact
S : Safe

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