57. Safety for Physical Human–Robot Interaction

Antonio Bicchi, Michael A. Peshkin, J. Edward Colgate

In this chapter, we report on different approaches to dealing with the problem of achieving the best performance under the condition that safety is provided throughout task execution. We also report on intelligent assist devices (IADs) that go beyond conventional notions of robot safety to protect human operators from harm, such as cumulative trauma disorders. However, IADs and other physical human–robot interaction (pHRI) devices are themselves generally powerful enough to cause harm. We argue that the differences between pHRI applications and conventional industrial manipulation requires that safety and reliability standards be rethought, and we offer a preview of the directions currently being undertaken by international standards committees.

We chapter discuss the new frontiers of robotic physical interaction with humans, describing motivations and applications of safe pHRI. The state of the art, and the technical challenges to develop new robotic systems for safe and effective collaboration with people, are discussed, subdividing the exposition into hands-off and hands-on pHRI systems. We present an overview of the applicable safety standards and their ongoing development.

Popular notions of robotics have long foreseen humans and robots existing side by side, sharing work, or even (as cyborgs) integrating into a greater whole. Until very recently, the reality has been quite different. Industrial robots have been far too dangerous to share space with humans, while physical interaction has (except in the case of telemanipulators, which date back to the 1940s) been far too unintuitive.

Shortly, all this is going to change radically: the next generation of robots will interact with people directly. Human–robot interaction (HRI) will certainly happen at the cognitive level (cHRI, Chap. 58), fundamentally concerning communication between human and robot through the many channels available to us (video displays, sounds, watching each other's motions, spoken language, or even gaze direction or facial expression). However, robots are distinct from computers in that they physically embody the link between perception and action. Hence, one of the most revolutionary and challenging features of the next generation of robots will be physical human–robot interaction (pHRI). In pHRI, humans and robots share the same workspace and come into contact with each other. Physical interaction may happen occasionally if normal operation is intended to be without contact, or on purpose if the operator is supposed to work in physical contact with the machine, exchanging forces and cooperating in action upon on the environment. We will designate these intended forms of interaction *hands-off* and *hands-on* pHRI, respectively.

pHRI robots will be designed to coexist and cooperate with humans in applications such as assisted industrial manipulation, collaborative assembly, domestic work, entertainment, rehabilitation or medical applications. Clearly, such robots must fulfill different requirements from those typically met in conventional industrial applications: while it might be possible to relax requirements on velocity of execution and absolute accuracy, concerns such as safety and dependability become of paramount importance when human lives are involved. This paradigm shift entails many differences in design and control, and opens up new challenging directions for research.

57.1 Motivations for Safe pHRI

Since the very beginning of industrial robotics, a great deal of attention has been paid to robot safety. The first line of defense has always been to take all measures to enforce segregation between robots and people. It is on such philosophy that most of the early technical literature on the topic of robotic safety is based [57.2–4], as well as the existing robotics safety regulations and standards [57.5–7]. However, the segregation paradigm fails in cases where the human and the robot must share the physical environment and in applications in which successful task completion requires collaboration.

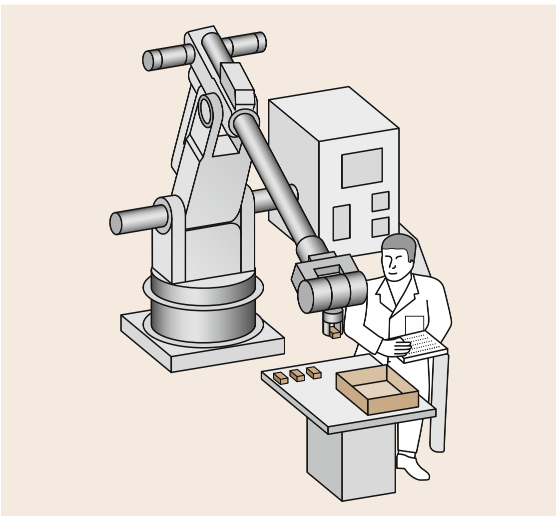

Fig. 57.1 Hazard in lead-through teaching [57.1]

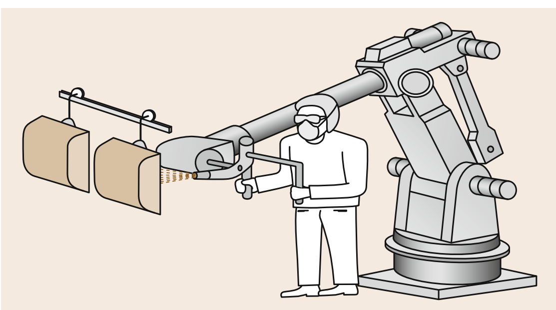

Fig. 57.2 pHRI in walk-through teaching [57.1]

Data on industrial robot-related fatalities indicate that, even in traditional applications of industrial robots, safety is not a solved problem – especially because of all the operational phases where the human operator is by necessity physically close to the mechanical arm or vehicle.

Studies reported in [57.1] show that *many robot accidents do not occur under normal operating conditions but instead during programming, program touch-up or refinement, maintenance, repair, testing, setup, or adjustment. During many of these operations the operator, programmer, or corrective maintenance worker may temporarily be within the robot's working envelope where unintended operation could result in injuries*.

People in the manufacturing environment are often injured even in the absence of robots, and curiously, this provides a major motivation for hands-on pHRI. Repetitive manual material handling exposes people to work-related musculoskeletal disorders (WMSD). In 1990, the average US worker's compensation expense for a lost-time back injury was $24 000 (source: National Council of Compensation Insurance). The ergonomics and productivity consequences are also documented for US industries: in 2004, over 400 000 WMSD were reported involving days away from work. Approximately one-third of these injuries were in the goods-producing industries, including manufacturing [57.8]. The total cost of these and related problems is of the order of $13–20 billion annually in the US alone. In many cases, robotic assistance could reduce WMSD drastically.

Market pressures together with ethical concerns are about to topple some of the barriers separating robots and people, and thus require a next generation of machines for safer pHRI. Consider for example the automotive industry. While the advent of robots has mitigated harsh, unsafe conditions in the body shop (where sheet metal is welded into a structure), and the paint shop, other areas have gone untouched for over three decades. The general assembly area, where the engine and cockpit subsystems and seats and tires are integrated with the painted shell, is such an untouched area. The tooling that has been used tends to be mechanical in nature and is primarily powered by human and pneumatic effort. Sensing and decision-making are the worker's responsibility. The principal reasons for not automating general assembly are both technical and economic. From a technological perspective, using robots for assembly in processes with high geometric dimensional variability is yet to be achieved with the reliability levels required for high-volume production. Further, programming complexity grows greatly with the number of trim options offered to the customer (e.g., leather seats, two-tone color, V6 engine, overhead console). Financially, the necessary increase in physical floor space dramatically impacts costs. In summary, the worker – with unsurpassed sensing and processing abilities – is a critical component in the assembly process. The primary concern, then, is that of the worker's well being, given that he/she tends to tire and is susceptible to injuries resulting from cognitive LAPSES and motor effort.

The case of general assembly explains why robots sometimes fail to replace people, but also motivates the close cooperation of robots and people. Humans have dense sensors (human tactile sensing especially outstripping attempts at emulation) and humans have an ability to interpret sensory data which artificial intelligence cannot approach. However humans have poor open-loop accuracy, tire easily, and are subject to repetitive stress injuries. In contrast robots have minimal sensing, not for lack of sensors but for their inability to interpret sensory input. However robots have high accuracy and speed and work indefinitely. Even with increasing sensorization, robots are not about to match a human's literally millions of sensory receptors.

The characteristics of robots and humans have led to a new generation of safe human-interacting machines known as intelligent assist devices (IADs). IADs are a class of robots intended principally for *comanipulation* of payloads along with a human partner. IADs serve principally to augment the strength of a human, but they may also serve to guide motion via virtual surfaces, tracking of a moving assembly line, or the like. Research and development into IADs is actively stimulated by automotive industries (General Motors and Ford Motor in the US, and Toyota in Japan taking the lead in the development of technologies and new standards). The value of robot–human collaboration is also being discovered in a variety of nonindustrial environments: from exoskeletons as human power amplifiers [57.9] or as haptic interfaces in virtual-reality environments [57.10], to medical assistants and telesurgery [57.11] in an operating room, to rehabilitation [57.12, 13] and robotic sports-trainers [57.14].

In the rest of this chapter, we will consider safety in two distinct cases of human–robot interaction: first, when physical contact occurs occasionally or by accident, and second, when physical interaction is an intentional part of planned operations.

57.2 Safety for Hands-Off pHRI

Management of risk for humans working near robots involves in general very broad considerations, ranging from potential electrical and pressurized fluid hazards, pinching hands or feet, dropping parts, etc. These however fall beyond the scope of this chapter, which focuses on the most dangerous risk specific to robots: the situation in which, in an unspecified instant during execution of a robot movement, a collision or unwanted force exertion occurs between the machine and a human.

Even under this restriction, the safety of pHRI involves several different aspects and depends on many factors, ranging from software dependability, to possible mechanical failures, to human errors in interfacing with the machine, etc. A thorough hazard analysis and risk evaluation must be performed according to specifically designed procedures: these methods are receiving a growing attention from the research community [57.15–18], international standardization bodies (Sect. 57.3), and industries. As an example, KUKA's *Safe Operation* and *Safe Handling* systems, incorporating Pilz's safety-related fieldbus, is currently in use at BMW's *Body in White* lines [57.19], and allows safe and redundant monitoring of the robot's position, velocity, and acceleration. Such a technology provides the basis for safe human–robot cooperation and can be used, e.g., for manual robot guidance with safely reduced speed. In the case of a malfunction (hardware or software) the robot is stopped immediately. Whether immediate stops are sufficient to guarantee safety, or even are the safest action to undertake, is not certain.

The *holy grail* of pHRI design is *intrinsic safety*: that is, a robot that will be safe to humans no matter what failure, malfunctioning, or even misuse might happen. Naturally, perfect safety against all odds is not feasible for machines which have to deliver performance in terms of weight lifting, swift motion, etc.: the trade-off between safety and performance is inherent to pHRI.

One important aspect of designing robots for safety is the ability to quantitatively assess the risk of injuries in accidents, so as to be able to compare different design and control solutions, and optimize them. We will focus here only on a particular aspect of safety of robot manipulators, that of unexpected collisions by the manipulator with a human operator, which in the worst case could happen anywhere on the manipulator structure and on the body of the operator and at any time during the execution of a planned trajectory. Much can be learned from the biomechanics of impacts in sports and automotive applications. In the relevant literature [57.20–22], several indices of the severity of an impact are proposed, which can be mapped (through extensive experimental campaigns and statistical correlations) to the probability of causing a certain level of injury. Among these are, e.g., Gadd's severity index (GSI), the 3 ms criterion, the viscous injury response (VC), and the thoracic trauma index (TTI). The most widely used index in the automotive industry is presently the so-called head injury criterion (HIC). Most of these indices are related to a basic *tolerance curve* developed at Wayne State University (the so-called WSTC) on the basis of data experimentally acquired from animal and cadaver head collision tests. The WSTC is a curve plotting head accelerations versus impact duration, indicating that very intense head acceleration is tolerable if it is very brief, but that much less is tolerable if the pulse duration exceeds 10–15 ms (as the time of exposure to cranial pressure pulses increases, the tolerable intensity decreases).

Gadd [57.20] plotted the tolerance limit curve in log–log coordinates, obtaining a straight line of slope ≈ 2.5, and proposed accordingly a severity index as

$$\mathrm{GSI} = \int_0^t a^{2.5}\,\mathrm{d}\tau\ ,$$

where a is the head acceleration (in g), and the integral is extended to the whole duration of collision. The head injury criterion (HIC) was proposed by *Versace* [57.22] as a refinement of the GSI, defined as

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

where T is conventionally the *duration* of the impact. As the choice of this duration is often difficult, it is recommended to consider the worst-case HIC at varying T. In general, both ends of the interval $T = (t_2 - t_1)$ are varied, and time t_2 is close to the time at which the head reaches its maximum velocity (typically, $t_2 - t_1 \leq 15\,\mathrm{ms}$). Generalizations of the HIC to collisions with other parts of the body have been proposed whereby the 2.5 exponent is replaced by other empirically determined values.

These metrics have constituted a useful basis for starting the development and evaluation of safe robotic concepts [57.23, 24]. The conditions under which these indices were formulated are quite different from those actually encountered in robotics. A recent experimental campaign [57.25] to measure the effects of impacts of a robot arm using standard crash-test facilities indicated that classical severity indices established in the automobile industry cannot be transferred without correction to the field of robotics. Indeed, the cited paper extrapolates experimental and simulation data to suggest that any robot, no matter how massive, whose parts are moving with a velocity of up to $2\,\mathrm{m/s}$, would not cause impacts with a HIC larger than ≈ 100, which is similar to what would occur to a person quickly walking and hitting a wall head first. Although such impacts, according to accepted standards in crash tests [57.26], would be considered to provoke only *very low injury potential*, they are still clearly unacceptable risks for a robot intended to coexist safely with humans.

57.3 Design of Intrinsically Safe Robots

Researchers have attempted to design intrinsically safer robots in various ways. The inherent danger of conventional robot arms might be mitigated by increasing their sensorial apparatus, using, e.g., proximity-sensitive skins such as those proposed in [57.27, 28], or by increasing the energy-absorbing properties of protective layers (adding enough soft and compliant coverings, or placing airbags around the arm, etc.).

An approach that has been intensively explored since the early 1980s is to design active force controllers, e.g., Salisbury's stiffness control or Hogan's impedance control schemes, to introduce compliance with respect to sensed interactions. However, these approaches may not prove robust with respect to impacts on portions of the arm that are not equipped with force/torque sensors. Also, it is well known in the robotics literature that there are intrinsic limitations to what the controller can do to alter the behavior of the arm if the mechanical bandwidth (basically dictated by mechanism inertia and friction) is not matched to the task [57.29]. In other

Fig. 57.3 The WAM robot (Barrett Technology Inc., Cambridge)

words, making a rigid, heavy robot behave gently and safely is an almost hopeless task, if realistic conditions are taken into account. Probably, the first arm with a lightweight structure intended for service applications was the whole-arm manipulator (WAM) proposed in [57.30].

The focus on safety has in recent years encouraged a number of technological innovations in actuators, sensors, and structural design, leading to impressive realizations such as the several generations of Deutsches Zentrum für Luft- und Raumfahrt (DLR) lightweight robots [57.31].

Fig. 57.4 The third version of the DLR lightweight robot (LWR-III) is capable of operating a payload equal to its own weight (13.5 kg)

Arms in this class are primarily characterized by a low inertia of their moving parts and back-drivability. The DLR LWRIII arm uses high-performance actuators and integrated torque sensors, which allow sophisticated control algorithms to be run. Significant joint compliance is often present in these arms as a side-effect of other design choices such as use of cable transmissions, harmonic drives, or joint torque sensors. Suitable force-control policies have been designed to employ such arms in safety-critical applications [57.32–35].

Another approach to increasing the safety level (and psychological acceptability) of robot arms interacting with humans is to intentionally introduce mechanical compliance into the design. By this measure, which complements low-inertia design of the arm's links and soft coverings, researchers can dynamically decouple the actuators' rotor inertia from the links whenever an impact occurs. Indeed, motors contribute most of the effective inertia in conventional geared drives, while direct-drive solutions remain impractical due to their large size and cost. Naturally, compliant transmissions can diminish performance, causing slow response, increased oscillations and longer settling times. However, this might not be a problem in some applications, e.g., entertainment. In most practical applications other than entertainment, however, positioning accuracy and velocity of task execution are crucial: controlling *soft* manipulators quickly and accurately – similarly to what humans do with their own arms – is one of the main avenues open in front of pHRI research.

The problem of controlling passively elastic joints so as to recover performance has been studied in depth in the robotics literature, both in the general case (see, e.g., [57.36, 37] and the review in [57.38]) and in safety-

Fig. 57.5 An entertainment robot by SARCOS physically interacting with a bystander. Compliance is built into the actuation system; accuracy and velocity are not primary goals

oriented design contexts [57.39, 40]. Adaptive control methods that could cope with uncertain inertia in robots with elastic joints have also been studied [57.41], although adapting to large, uncertain stiffness parameters appears to be an open problem.

It can be expected that the promptness of an elastically actuated arm is intrinsically severely reduced, if compliance is high enough to be effective for safety. In other words, even if optimal methods for controlling very compliant arms were available, there are inherent limitations on performance imposed by such hardware. To overcome these limitations, a recent trend in intrinsically safe robotics advocates the co-design of the mechanics and control of passively compliant, yet fast, strong, and accurate arms.

Very compliant transmissions may ensure natural and safe interaction but be inefficient in transferring energy from actuators to the links for fast motion. An approach to reducing the inertia of a manipulator arm for safety, while preserving performance, is distributed macro–mini actuation (DM2) [57.23, 42]. For each degree of freedom (joint), a pair of actuators is employed, connected in parallel and located in different parts of the manipulator. The key of the macro–mini actuation approach is to divide the torque generation into separate low- and high-frequency components which sum in parallel, according to an idea originally proposed in [57.43]. Gravity compensation and other large but slowly time-varying torques are generated by a *series elastic actuator* (SEA) [57.39] consisting of a relatively large actuator located at the base of the manipulator and connected to the axis through a spring, thus achieving low overall impedance. For the high-frequency torques needed, small motors collocated at the joints are used, providing high-performance motion while not significantly increasing the combined impedance of the manipulator–actuator system.

A different approach to gain performance for guaranteed-safety joint actuation is to allow the mechanical compliance (or, more generally, the impedance) of motion transmission devices to vary during the execution of tasks. As often, an inspiration can be taken from nature, with the human arm representing an instance of a powerful, agile manipulator that is at the same time safe and capable of high delicacy. The example from nature suggests that *variable compliance* can be extremely useful towards the goal of safe and fast motion: humans can vary the compliance of their arm for different tasks, and even during different phases of a task [57.44]. Unless it is intentionally used to harm, the human arm is typically controlled to move slowly when it is stiff, and to be compliant while moving fast. This behavior also shows how the safety–performance trade-off can be addressed not by mere mechanical means, nor by control strategies alone, but by the intimate combination of the two aspects.

The idea of adapting the mechanical compliance of a robot arm to the task is almost as old as robotics itself ([57.45]) and has seen numerous implementations in different guises. Among the designs oriented towards physical human–robot interaction, we mention the mechanical impedance adjuster (MIA) [57.46] adopted in the humanoid robot WENDY, which uses a variable-length leaf spring. The MIA can realize a wide range of compliance values to adapt to different tasks in pHRI. However, similarly to many other such devices, the design mainly aims at adapting the compliance to a given task before the execution of the task itself, and keeps it constant during motion.

A different approach, called variable-impedance actuation (VIA) [57.24, 47] proposes a mechanical/control co-design that exploits rapid and continuous variations of transmission impedance during task execution (by varying its stiffness, damping, or gear ratio), so as to provide low levels of injury risk at any time during motion and minimize negative effects on control performance.

The trade-off between safety and performance also involves task motion planning. For a mechanism with given total inertia and actuator torque limits, one can formulate an optimal control problem to be used for comparing mechanical/actuation alternatives at their best possible performance. This question can be formalized as a minimum-time optimal control problem (i. e., a problem in the class of the so-called *brachistochrones*), specified for given initial and final positions of the joints and of the motors, and has to be computed taking into ac-

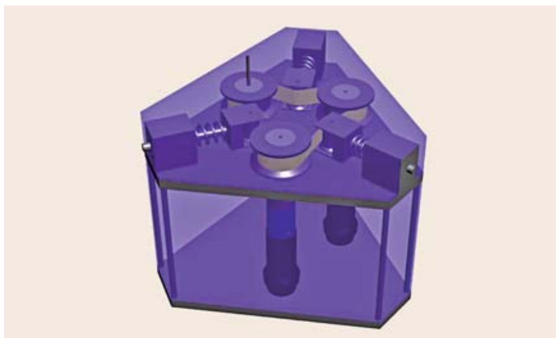

Fig. 57.6 The variable stiffness actuator of the University of Pisa implements the VIA approach by an antagonistic arrangement of nonlinear springs

count the limits on maximum motor torque and the lower and upper bounds to available transmission impedance. Admissible trajectories must satisfy a safety condition, which is expressed as a function of the velocities of the manipulator, its configuration, and the amount of inertia that is reflected on the links through the compliant transmission.

Solutions to such a *safe brachistochrone* problem for a single-joint actuator-link VIA system were obtained by numerical optimization in [57.24], showing that the optimal control policy consists of imposing high stiffness at low speeds (when the link needs accuracy and control authority to accelerate promptly), while low stiffness should be used at high speeds, to reduce the effect of the reflected motor inertia in the initial instants of impact. Such a *stiff and slow/soft and fast* control paradigm for VIA systems matches well with physical intuition (most of the motion energy transfer from the motor should occur during the initial and final acceleration/deceleration phases), and with the natural control inspiration. Although no solutions are known to the multilink safe brachistochrone problem to date, ideal solutions obtained for a single joint can provide guidelines to be used also for more complex systems. The VIA concept can be realized though different arrangements, including the relocation of actuators close to the robot base and transmission of motion through steel cables and pulleys, the use of parallel and distributed macro–mini actuation with elastic couplings, the use of antagonistic actuation schemes, etc.

Once a collision has occurred, and its primary impact effects have been possibly reduced by mechanical design, further injuries can be avoided by a suitable reflex control action. A collision detection scheme based on the command inputs and sensor outputs available on the robot should trigger the switching of the control law [57.48, 49]. A physical collision can be treated as a fault condition of the robotic device. Accordingly, methods and algorithms available for the so-called fault detection and isolation problem [57.50] have recently been applied to robot collision detection [57.51, 52]. Their integration into a safety-oriented controller and their extension to the case of (possibly time-varying) compliant robot arms is an open issue for research.

Part G | 57.4

57.4 Safety for Hands-On pHRI

A different set of safety methods and strategies are required in cases where successful task completion requires people and robots to collaborate intimately. This is the case for intelligent assist devices (IADs), human extenders, and collaborative robots (cobots).

IADs have their roots in *Ralph Mosher's* famous Handiman and Hardiman projects of the 1960s [57.54]. It was the initiative of General Motors (GM), however, that led to further active development in the mid 1990s.

Fig. 57.7 Fanuc's IAD for moving engine blocks [57.53]

Beginning in 1995, GM began to work with two groups: Kazerooni at University of California (UC) Berkeley and Colgate and Peshkin at Northwestern University. The Ford Motor Company also encouraged the participation of Fanuc Robotics, an established robotics supplier to the automotive industry. The automotive emphasis of the program helped steer the results toward applicability to general assembly (Sect. 57.1).

Fanuc developed a prototype gantry-type robot with force-input handles for human guidance, to be used at Ford to install truck instrument panels on a moving assembly line or to load cylinder heads on top of engine blocks. Fanuc's IAD possessed six powered admittance-controlled axes, like a conventional industrial robot. It was driven however by force inputs from a human user who could exert command forces on force-sensitive handles that moved with the end-effector. This is a key distinction from remote joystick or force-input devices that do not move with the payload. Operator motion together with the payload gives the operator immediacy to the task and to the motions of the robot, and even some haptic feedback from the task. In contrast, teleoperation produces distancing from the task that generally requires great cognitive effort to overcome, and leads to reduced speed. Additionally, a proximate operator can

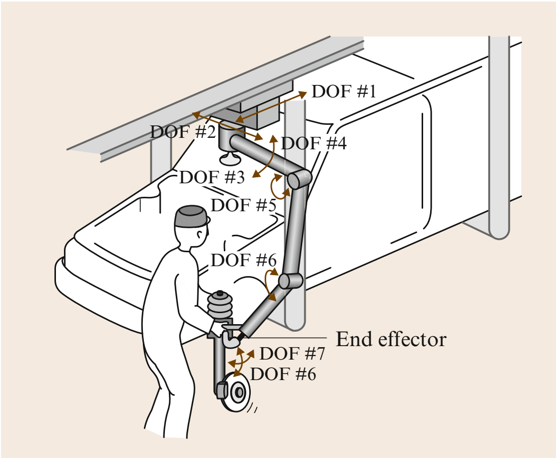

Fig. 57.8 Toyota's skill assist system [57.55]

Fig. 57.9 pHRI in human power amplifiers [57.56]

detect and correct minor issues, such as a cable bundle that has draped the wrong way and needs to be moved. In addition the Fanuc IAD was able to implement virtual guides and walls, to be used as a *funnel* shape that assisted with moving a payload through an automobile door opening without collisions.

At the Toyota Motor Company, a similar concept, known as the skill assist, was developed at the end of the 1990s. A distinctive feature of this device was that the dynamic behavior of the assistive mechanical manipulator was varied according to the task phase. This approach was based on two observations. First, it was observed that the dynamic behavior preferred for moving a payload over long distances was primarily inertial, while the dynamic behavior preferred for precise positioning was primarily viscous. Second, it was observed that the phase of the task – start up, traversing, or fine positioning – could be automatically determined based on motion characteristics. Experiments performed with the skill assist showed significant improvements (reduction) in operator force (primarily for stopping), task completion time, and operator subjective impression.

Less structured types of IADs applications can be approached by the concept of human extenders [57.56], which emphasize amplification of human force and reach, such that for instance a human can grasp and lift a box that would otherwise be too wide and too heavy. Extenders may take the form of a robot arm or leg, or can even be worn by the user in the form of exoskeletons [57.9].

In industrial practice, it is much more common to support a payload from a cable or chain than from a rigid-link mechanism. Cables and chains have many advantages: they permit relatively free rotation about a vertical axis as well as small horizontal motions (or larger horizontal motions when supported by an articulated arm or crane), they have low inertia, low cost, and provide minimal obstruction. However, it is difficult to implement power assist with cable-based systems. Kazerooni built on his work with extenders to develop a servo-controlled lift assist that is marketed by Gorbel, Inc. under the trade name G-Force. The key innovation of the G-Force was a slide handle inline with the cable that provided an intuitive input: sliding up to move up, and down to move down. Speed could be easily controlled.

Northwestern University's spin-off company Cobotics, Inc. (which was later acquired by the Stanley Assembly Technology division of StanleyWorks, Inc.) went a step further to develop the iLift and iTrolley modules that could be combined into a multiaxis human-assist crane. A key innovation was a cable angle sensor that could detect small departures of the cable from vertical, and use this to provide direction and speed commands to the iTrolleys, which provided motion in a horizontal plane in the manner of an overhead crane.

At this juncture it is worth noting that, while most of the IADs described so far have the structure illustrated

a)

Operator ---- IAD ---- Workpart

b)

Operator ---- Workpart ---- IAD

Fig. 57.10 **(a)** Structure in which the IAD is interposed between the operator and the workpart. **(b)** Structure allowing the operator to place hands directly on the workpart

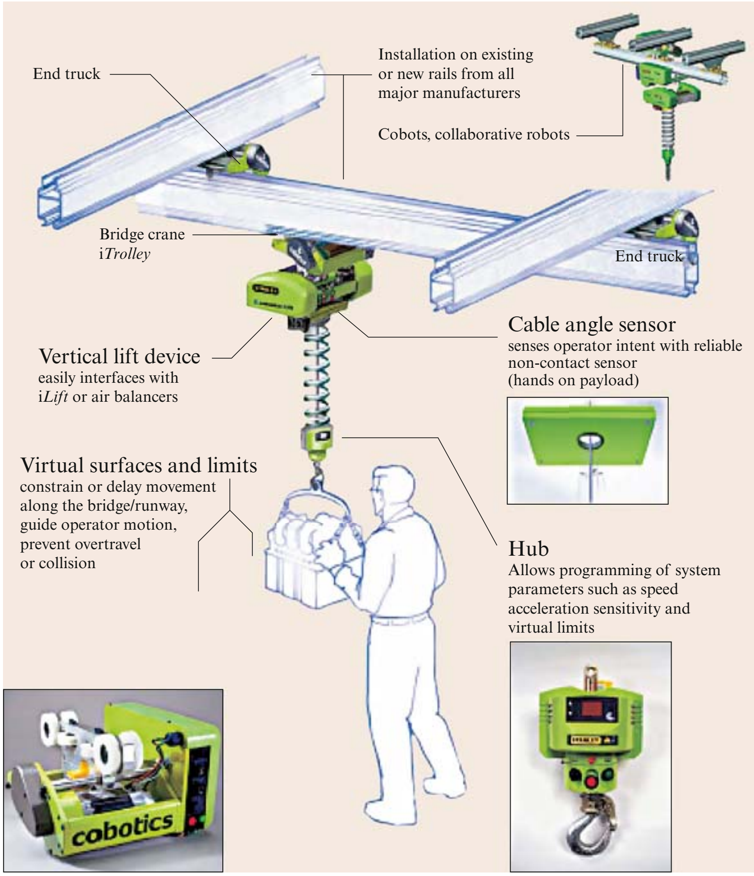

Fig. 57.11 The Stanley Cobotics modular system including lift assist, cable angle sensor, and powered trolleys

in Fig. 57.10a in which the IAD is interposed between the operator and workpart, cable-based systems are particularly amenable to the structure in Fig. 57.10b. Here, the operator manipulates the workpart directly while the IAD assists. The latter structure is often denoted *hands on payload*.

The iTrolley system illustrated in Fig. 57.11 is an example of *hands on payload*: the operator pushes on the workpart and the overhead crane follows. The strengths and weaknesses of this approach are evident. On the one hand, the operator is in intimate contact with the workpart, enabling highly intuitive movement. On the other hand, the cable can at best remain vertical at all times, contributing zero force to moving the workpart. If the cable were to *lead* the motion, the overall behavior would be unstable.

Nonetheless, *hands on payload* can provide a significant ergonomic advantage as the *pull test* data in Fig. 57.12 illustrate. Here, a subject pulled a variety of different payloads rapidly from a fixed starting location to a fixed stopping location and his forces were recorded. Tests were run with traditional passive trolleys and with iTrolleys. The data show that the starting forces are modestly reduced with the iTrolley (because the iTrolley contributes to accelerating the overhead crane), and that the stopping forces are dramatically reduced (because the iTrolley eliminates overshoot of the overhead crane). This example illustrates an important point: IADs may be as valuable in moving the support structure as in moving the workpart itself.

Cobots – collaborative robots [57.13, 57, 58] – are a distinct approach to relieve humans from fatigue, stress, and injuries in manipulating heavy and/or awkward parts. Cobots presume a division of control between human and robot, with a robot perhaps supporting a payload and allowing a human to guide it, subject to constraint surfaces or virtual walls. Cobots are specifically designed to produce virtual guiding surfaces: software-defined paths or surfaces that constrain or direct the motion of the payload for the purpose of

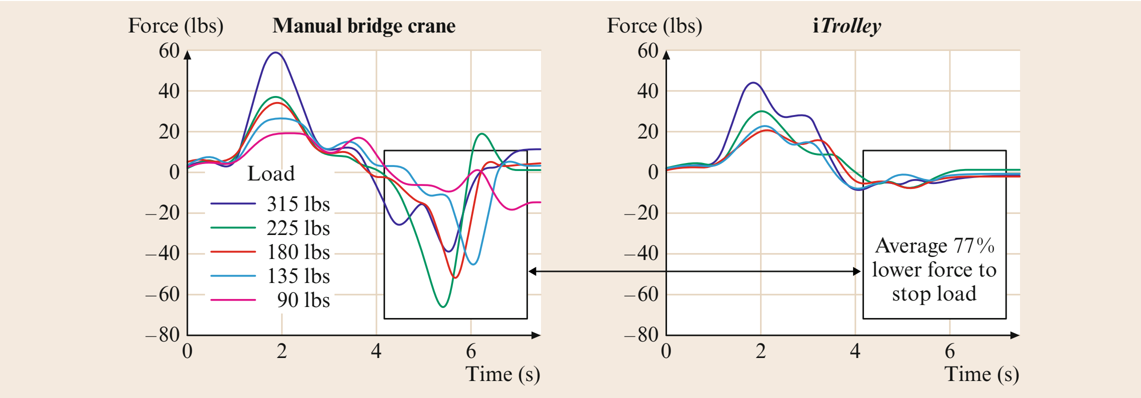

Fig. 57.12 Data from a set of pull tests showing the impact of the iTrolley and cable angle sensor on starting and stopping forces for various payloads

Fig. 57.13 The simplest cobot consists of a single rolling wheel on an *xy* frame [57.57]

Fig. 57.14 A cobot assisting a human in assembling a car door

guidance. Ergonomic as well as productivity benefits result from combining the strength and computer interface of the cobot with the sensing and dexterity of the human worker.

Consider the cobot shown in Fig. 57.13. A computer controls the steering of the wheel, thus confining the operator's handle to whatever virtual surfaces and free spaces are desired. In contrast to extenders and Fanuc's IADs, however, in the remaining direction – in this case the rolling path that the computer allows – the operator is in direct physical connection with payload; there is no sensor–actuator pair to interfere with the haptic sense between the payload and the operator. Additionally since computers only steer and do not drive the cobot forward, an element of inherent safety is introduced. The cobot concept has been extended to multiple degrees of freedom: Fig. 57.14 shows a planar cobot, used for door handling at GM.

The cobot base permits planar motions on the floor (x, y, and rotation). The cobot indexes itself to the automobile's running board and guides the operator and payload (a door) along a path that brings the payload into proper alignment with the hinge axis of the automobile.

Cobots can also display the types of behavior mentioned above: free mode, in which the wheels are steered so as to comply with user forces; path mode, in which the cobot steers along a defined path through 3-space; and virtual surface mode in which the wheels are steered tangent to a software-defined constraint surface, resisting user forces that would violate the virtual surface.

57.5 Safety Standards for pHRI

In practice, standards are an important means of addressing and solving safety problems in the workplace, as well as encouraging the adoption of new and unfamiliar technology. Research work in the robotics industry and academia is both influenced by current work on standards, and has an influence on their evolution – which is particularly interesting at present.

The present landscape for robotics standards include well-established national standards (ANSI-RIA for the US, CSA in Canada, DIN in Germany, etc.), that are collected and harmonized by the International Organization for Standardization (ISO). Safety for industrial robots are addressed both by general standards on safety of machinery (e.g., ISO 12100:2003 *Basic concepts, general principles for design*; ISO 13849:1999 *Safety-related parts of control systems*; ISO 13855, *Positioning of protective equipment with respect to the approach speeds of parts of the human body*), and by robot-specific standards. The main ISO safety standard for robots is ISO 10218, which dates back to 1992 [57.6]. In 2002 a revision of the standard was undertaken. Work has been ongoing since, gradually turning what started as a simple harmonization effort into a genuine development effort introducing new and exciting concepts to the world of industrial robot safety [57.59]. The revised ISO 10218 (*Robots for industrial environment – Safety*) will be a two-part document. Part 1, entitled *Robot*, was published in 2006 [57.60]. Part 2, on which work has just begun, has a working title of *Robot System and Integration* and is not available at the time of writing. Part 2 is intended to address workplace safety requirements and is directed more to the end-user than the manufacturer.

The most salient changes of the 2006 standard revision are:

1. *new modes of operation*: the standard finally allows the introduction in the workplace of advanced robotics concepts, such as *simultaneous control* of multiple manipulators, as, e.g., in the master–slave configurations; *mobile* robots mounted on vehicles for industrial automation, and (most relevant to this chapter) *collaborative operation* in which purposely designed robots work in direct cooperation with a human within a defined workspace with the operator;
2. *control reliability*: while former standards placed reliance upon hardwired electromechanical components, the revised one allows *safety-rated soft-axis and space-limiting* control circuitry to use state-of-the-art software, electronic, and network-based technology (including wireless);
3. *safeguarding and clearance*: instead of fixed safeguard distance, these can be evaluated based on the assessment of stopping time and distance to be provided by the robot manufacturer in different load conditions. In collaborative mode, hard limits on either the maximum dynamic power (80 W) or maximum static force (150 N) at the end-effector apply, as well as on its maximum velocity (250 mm/s).

Although the revision of ISO 10218 is already taking into consideration many more advanced features than in the past, evolution is still ongoing. In particular, in the domain of hands-on pHRI, the American National Standards Institute (ANSI) has established a committee, T-15, that has published a draft safety standard for intelligent assist devices (IADs) [57.61]. The committee defined IADs as *single- or multiple-axis devices that employ a hybrid, programmable, computer–human control system to provide human strength amplification, guiding surfaces or both*. Notable aspects of the standard include:

1. Risk assessments replace fixed rules: instead of declarations regarding how to accomplish safe operation, risk assessment procedures were advised for IAD and pHRI robotic technologies, to identify and mitigate risks in proportion to their seriousness and probability;
2. Safety-critical software: the greater complexity of human–robot interaction, and the observation that an abrupt power-down is not always a safe solution, necessitate a greater reliance on safety-critical software rather than safety-critical hardware. The T-15 draft standard requires that software- and firmware-based controllers shall, under any single component failure, lead to the shutdown of the system in a safe state, maintenance of a safe load position, and the prevention of subsequent automatic operation. For example, this degree of safety may be achieved by using microprocessor redundancy, microprocessor diversity, and self-checking;
3. Dynamic limits: physical limits of people are taken into account by requiring that operators be able to *outrun, overpower, or turn off* IADs. Speed must not exceed 2.0 m/s, a fast walk; overforce or overload devices or techniques must be used that can reliably detect an impulse force of 267 N (60 lbf) (the committee dictated that a human operator should win

a fight). These and similar limits could be further reduced to the extent practical as determined by a risk assessment;

4. Emergency stops: sole reliance on the traditional red mushroom e-stop button was felt to create a hazard. For instance, in some unexpected situations one might want an IAD to continue to actively *track* a moving vehicle, rather than come immediately to a halt and possibly drag a part and a person engaged in a moving line. The T-15 draft standard demands a traditional e-stop, but also permits *an IAD may have one or more context-based safety stop circuits. When used, inputs should be provided to allow application-specific external devices to initiate context-based safety stops;*
5. Man–machine interface: IADs may operate in different modes (free mode, hands-on-controls, hands-on-payload, line tracking, etc.). The T-15 committee found that *mode misunderstanding* was a likely cause of safety problems. IADs should have few modes, well understood by their operators, well communicated to the operator (*what mode is this IAD in?*) and well commanded by the operator to the IAD (*go into free mode!*).

57.6 Conclusions

The next generation of robots will coexist with humans and will interact with us physically. In this chapter we have illustrated some of the motivations and economic factors that are pushing this revolution forward. A robot arm that is to interact with humans must place safety at a premium as a design consideration. As Asimov's laws of robotics have it 'A robot may not injure a human being...', or, to rephrase the science fiction author, under no circumstances should a robot cause harm to people, directly or indirectly, in regular operation or in failures. Another requirement on robot manipulators remains their performance: their accuracy and speed in performing tasks as required.

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