Chapter 12
Collaborative Robots

In 1942 Isaac Asimov published the science fiction novel "I, Robot", where the three laws of robotics were introduced. First rule stated that "A robot may not injure a human being or, through inaction, allow a human being to come to harm".

Until now, industrial robots have always been fast and robust devices that work on specific tasks designed for them. To stay in accordance with the aforementioned rule they were performing behind fixed and interlocked guards and sensitive protective equipment to prevent human intrusion into their workspace. With the introduction of collaborative robots the cages are omitted as those robots are designed to work with humans. They are built with different safety features to prevent collisions, but if a collision occurs, the mechanism will move in the opposite direction or stop completely to avoid causing injury.

The technical specification ISO/TS 15066:2016: Robots and robotic devices—Collaborative robots supplements the requirements and guidance on collaborative industrial robot operation provided in ISO 10218-1:2011 and ISO 10218-2:2011 (ANSI/RIA R15.06:2012). It specifies safety requirements for collaborative industrial robot systems and the work environment. Specifically, ISO/TS 15066:2016 provides comprehensive guidance for risk assessment in collaborative robot applications.

12.1 Collaborative Industrial Robot System

A collaborative robot is a robot that can be used in a collaborative operation, where a purposely designed robot system and a human operator work in direct cooperation within a defined workspace. The term robot defines robot arm and robot control and does not include the robot end-effector or part. With the term robot system we describe robot, end-effector, and workpiece.

For the collaborative robot system we can define different workspaces (Fig. 12.1):

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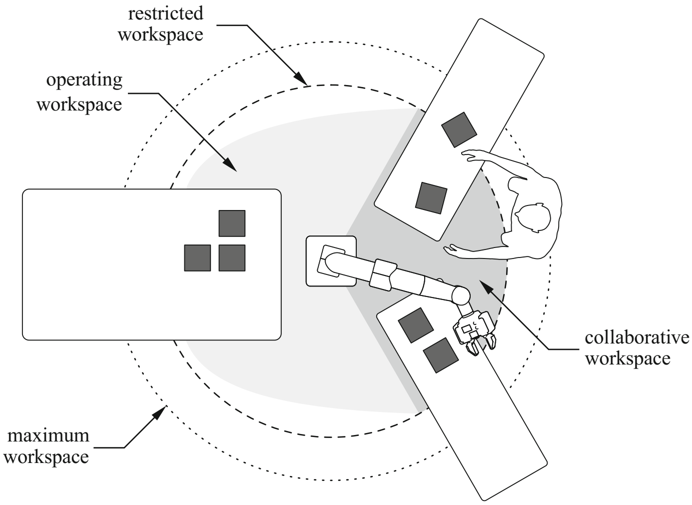

Fig. 12.1 Maximum workspace (limited by dotted line), restricted workspace (limited by dashed line), operating workspace (grey areas), and collaborative workspace (dark grey area)

- maximum workspace: space which can be swept by the moving segments of the robot as defined by the manufacturer plus the space which can be swept by the end-effector and the workpiece;
- restricted workspace: portion of the maximum space restricted by limiting devices that establish limits which will not be exceeded;
- operating workspace: portion of the restricted space that is actually used while performing all motions commanded by the task program;
- collaborative workspace: portion of the operating space where the robot system and a human can perform tasks concurrently during production operation.

The collaborative workspace must be designed in a way that the operator can perform all intended tasks. The location of machinery and equipment should not introduce any additionally safety hazards. In the collaborative workspace strict limitations about the speed, space limits, and torque sensing are applied to guarantee operator safety. Outside the collaborative workspace the robot can act as a traditional industrial robot without any particular limitations excluding those that are task-related.

The term operator includes all personnel that are in contact with the robot system, not only production operators. It includes maintenance, troubleshooting, setup, cleaning, and production personnel.

The operational characteristics of collaborative robot systems are significantly different from those of traditional industrial robot system presented in ISO 10218-1:2011 and ISO 10218-2:2011. In collaborative robot operations, operators can work in direct proximity to the robot system while the system is active, and physical contact between an operator and the robot system can occur within the collaborative workspace. As such, adequate protective measures must be introduced to collaborative robot systems to ensure the operator's safety at all times during collaborative robot operation.

12.2 Collaborative Robot

The design of collaborative robots is moving away from heavy, stiff, and rigid industrial robots towards lightweight devices with an active and/or passive compliance. The use of lightweight high-strength metals or composite materials for robot links contributes to small moving inertia which further affects the power consumption of the motors. Serial manipulators can be equipped with high power/torque motors with high transmission ratio gears in each joint or have motors positioned at the base while the power is transferred via tendons. If the transmission ratio is small the system is inherently back-drivable.

Use of intrinsically flexible actuators enables the design of biologically inspired robots, as the actuators mimic the performances of human/animal muscles. The actuators can have fixed mechanical impendence controlled via active control, such as series elastic actuator (SEA), or the impedance can be adjusted by changing parameters of a mechanical joint, as in variable stiffness actuator (VSA). SEA is a combination of motor, gearbox, and a spring, where the twist of the spring is measured to control the force output, while that measurement of the twist of the spring is used as a force sensor. VSA can be used to make the robot safer in the case of collision as the joint stiffness and impact inertia are reduced. Conceptual designs of SEA and VSA are presented in Fig. 12.2.

Collaborative robots also have special geometries that minimize the contact energy transfer by maximizing the impact area. Robots have round shapes and integrated features that reduce the risk of pinch points and the severity of an impact. Main features of the collaborative robot are presented in Fig. 12.3

To ensure a high level of safety, the robot system must include different sensors for monitoring the state of the robot and its workspace as presented in Chap. 7. Robots can be equipped with joint torque sensors, force/torque sensors at the end-effector, and different tactile sensors used as a soft skin or a hard shell for the robot. All these sensors enable the robot to detect contact with the environment (operator) or avoid collision by anticipating it and responding accordingly. Some robots use

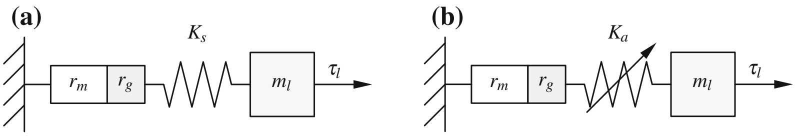

Fig. 12.2 **a** Series elastic actuator (SEA), **b** variable stiffness actuator (VSA); r_m and r_g represent motor and gearbox, K_s compliant element with fixed stiffness, K_a adjustable compliant element, m_l moving link's mass, and τ_l joint torque resulting in link movement

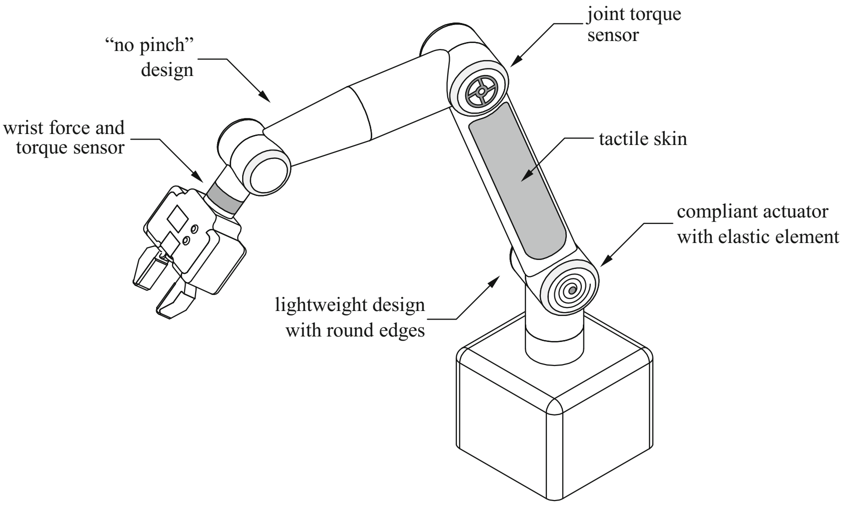

Fig. 12.3 Design features of a collaborative robot

redundant encoders in every joint to substitute for expensive joint torques; force can be derived from the known motor current and joint position. Robot systems can include other safety rated sensors, e.g., safety cameras, laser scanners, laser curtains, safety mats and other electro-sensitive protective equipment, to detect the presence of the operator in the robot surroundings. This information can be then used for a proper robot response to prevent clamping, compression, or crushing of the operator.

The incorporated sensors can be used for safe control of the robot. The main paradigm is how to handle physical contact between the mechanism and the surroundings. One of the most popular control schemes is impedance control, that is based on the dynamic robot model (5.56). The dynamic model is used to assess the necessary joint torques for proper robot movement. If the measured joint torques deviate from the assessed one, then the difference is detected as a collision. When a collision has been detected, the proper response strategy should be activated to prevent potential danger to the operator. The robot can ignore the contact and follow the reference trajectory, or the robot can be stopped. Other possibilities include switching from position control to zero-gravity torque control (very high compliancy of the robot), switch to torque control with the use of signals from joint torques to minimize link and motor inertia (even “lighter” robot), or to use external measured torques and switch to admittance control, where robot and collided object act as two magnets facing with the same poles together.

The objective of collaborative robots is to combine the best of robots and of human operator: the robot’s precision, power, and endurance coupled with the human operator’s excellent capability for solving imprecise problems. As the robot and the operators are collaborating in the same workspace, contact between robots and humans is allowed. If an incidental contact does occur, then that contact should not result in pain or injury. As such, collaborative robots can be used alongside operators and enhance the productivity of the workers. Robots are lightweight and have a small footprint so can be easily moved around workshop, thus increasing their versatility. Programming of collaborative robots is simple, mostly done by hand guiding, so the use of the robot is very flexible; the robot can be operational at a new workstation in a very short time.

12.3 Collaborative Operation

Collaborative operation is not defined with the use of the robot alone but is conditioned by the task, what the robot system is doing, and the space in which the task is being performed. Four main techniques (one or combination of more) can be included into collaborative operation:

- safety-rated monitored stop;
- hand guiding;
- speed and separation monitoring;
- power and force limiting.

With all four techniques the robot performs in automatic mode. The main details of all four methods are presented in Table 12.1. More detailed descriptions are available further below.

Table 12.1 Types of collaborative operations

	Speed	Torques	Operator controls	Technique
Safety-rated monitored stop	Zero while operator is in collaborative workspace	Gravity and load compensation only	None while operator is in collaborative workspace	No motion in the presence of the operator
Hand guiding	Safety-rated monitored speed	As by direct operator input	Emergency stop, enabling device, motion input	Motion only by direct operator input
Speed and separation monitoring	Safety-rated monitored speed	As required to maintain min. separation distance and to execute the application	None while operator is in collaborative workspace	Prevented contact between the robot system and the operator
Power and force limiting	Max. determined speed to limit impact forces	Max. determined torque to limit static forces	As required by application	Robot cannot impart excessive force (by design or control)

12.3.1 Safety-Rated Monitored Stop

In this method the robot system must be equipped with safety-rated devices which detect the presence of the operator inside the collaborative workspace (e.g., light curtains or laser scanners). The operator is permitted to interact with the robot system in the collaborative workspace only when the robot's safety-rated monitored stop function is active and the robot motion is stopped before the operator enters the shared workspace. During collaborative task the robot is in standstill with the motors powered. Robot system motion can resume only when the operator has exited the collaborative workspace. If there is no operator in the collaborative workspace, the robot may operate as classical industrial robot, e.g., non-collaboratively.

The operations of the safety-rated monitored stop are presented in Table 12.2. When the operator is outside the collaborative workspace the robot can perform without any limitations. But in the case that the robot is present in the workspace at the same time as the operator, the robot's safety-rated monitored stop should be active. Otherwise the robot must engage category 0 protective stop (uncontrolled stop of the robot by immediately removing power to the actuators) in case of fault (IEC 60204-1).

This method can be applied to applications of manual loading or unloading of end-effector, work-in-progress inspections, and applications where only one moves in collaborative workspace, (e.g., robot or operator). Safety-rated monitored stops can also be integrated with other collaborative techniques.

12.3.2 Hand Guiding

For hand guiding the robot must be equipped with a special guiding device located at or near the robot end-effector that serves for transmitting motion commands to the robot system. The device must incorporate an emergency stop and an enabling device unless the robot system meets inherently safe design measures or safety-limiting functions. The location of the guiding device should enable the operator to

Table 12.2 Robot actions for safety-rated monitored stop

		Operator's proximity to collaborative workspace	
		Outside	Inside
Robot's proximity to collaborative workspace	Outside	Continue	Continue
	Inside and moving	Continue	**Protective stop**
	Inside, safety-rated monitored stop	Continue	Continue

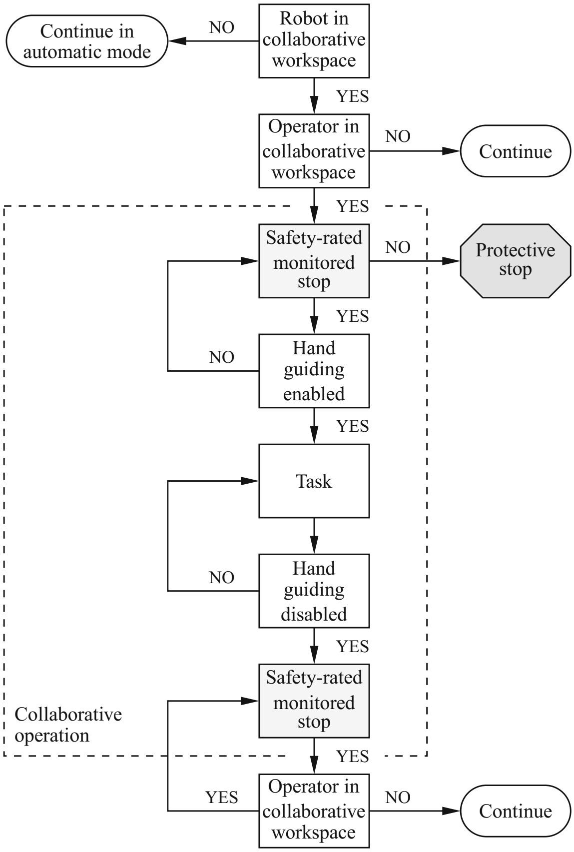

Fig. 12.4 The operating sequence for hand guiding

directly observe the robot motion and prevent any hazardous situations (e.g., operator is standing under heavy load). The control of the robot and end-effector should be intuitively understandable and controllable.

The robot system is ready for hand guiding when it enters the collaborative workspace and issues a safety-rated monitored stop. At this point the operator can enter the collaborative workspace and take control of the robot system with the hand guiding device. If the operator enters the collaborative workspace before the system is ready for hand guiding, a protective stop must be issued. After the safety-monitored stop is cleared the operator can perform the hand guiding task. When the operator releases the guiding device the safety-rated monitored stop is issued. Non-collaborative operation resumes when the operator leaves the collaborative workspace. The operating sequence for hand guiding is presented in Fig. 12.4.

This collaboration technique is suitable for implementation within applications where the robot system acts as a power amplifier, in highly variable applications, where robot system is used as a tool, and in applications where coordination of manual and partially automated steps is needed. Hand guiding collaboration can be successfully implemented into limited or small-batch productions.

12.3.3 Speed and Separation Monitoring

In this method the operator and robot system may move concurrently in the collaborative workspace. During joint operations, the minimum protective separation distance between the operator and robot system is maintained at all time. Protective separation distance is the shortest permissible distance between any moving hazardous part of the robot system and operator in the collaborative workspace.

The protective separation distance S_p at time t_0 can be described by (12.1):

$$S_p(t_0) = S_h + S_r + S_s + C + Z_d + Z_r \,, \tag{12.1}$$

where S_h is the contribution to the protective separation distance attributed to the operator's change in location. The formula takes into account the braking distance S_r, which is the distance due to the robot's reaction time, and S_s describing the distance due to the robot system's stopping distance. C presents the intrusion distance, which is the distance that a part of the body can intrude into the sensing field before it is detected. The protective separation distance S_p also includes the position uncertainty of the operator Z_d, resulting from the sensing measurement tolerance, and the position uncertainty of the robot system Z_r, resulting from the accuracy of the robot position measurement system. The maximum permissible speeds and the minimum protective separation distances in an application can be either variable or constant. The various contributions to the protective separation distance are illustrated in Fig. 12.5.

The robot must be equipped with a safety-rated monitored speed function and a safety-rated monitored stop. The robot system includes also additional safety-rated peripheral for human monitoring (e.g., safety-rated camera systems). The robot system can maintain minimum protective separation distance by speed reduction, which could be followed by safety-rated monitored stop, or execution of an alternate path which does not violate the protective separation distance, as presented in Fig. 12.6. If the actual separation distance between the robot system and the operator falls below the protective separation distance, the robot system should initiate a protective stop and initiate safety-related functions connected to the robot system (e.g., turn off any hazardous tools). When the operator moves away from the robot, the actual separation distance meets and exceeds the protective separation distance; at this point the robot can resume motion automatically.

Speed and separation monitoring is useful in applications where robot system's and operator's tasks run simultaneously.

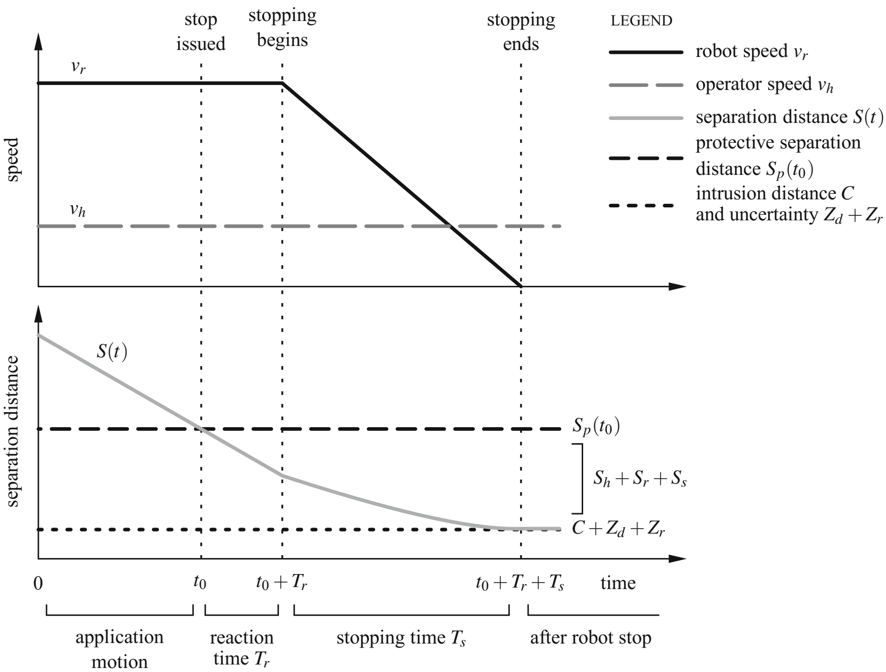

Fig. 12.5 Graphical representation of the contributions to the protective separation distance between an operator and a robot

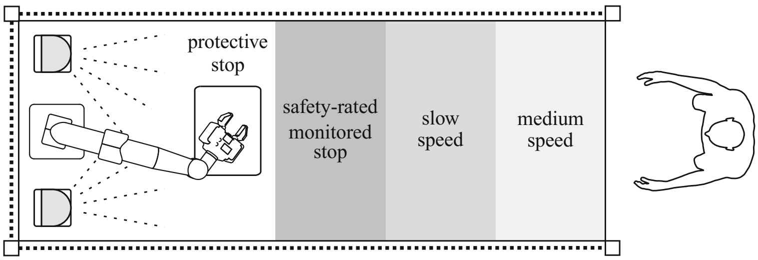

Fig. 12.6 Safety-rated levels for maintaining minimum protective separation distance

12.3.4 Power and Force Limiting

The method of power and force limiting allows physical contact between the robot system and the operator, that can occur either intentionally or unintentionally. The method demands that robots be specifically designed by means of low inertia, suitable geometry (rounded edges and corners, smooth and compliant surfaces), materials (padding, cushioning, deformable components), and control functions. The former includes active safety design methods, such as limiting forces and torques,

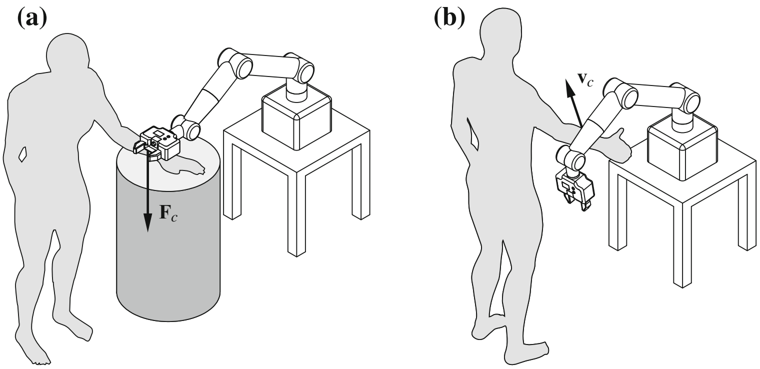

Fig. 12.7 **a** Quasi-static and **b** transient contact

limiting velocities of moving parts, limiting momentum by limiting moving masses, and limiting mechanical power or energy as a function of masses and velocities. The design of the robot can also include use of safety-rated soft axis, space limiting functions, and safety-rated monitored stop functions. Some robots also include sensing to anticipate or detect contact.

The contact between the collaborative robot and operator's body parts could be:

- intended as part of the application sequence;
- incidental due to not following the working procedure, but without technical failure;
- a failure mode that leads to contact situations.

There are two possible types of contact between moving part of the robot system and areas on the operator's body. The *quasi-static* contact (Fig. 12.7a) includes a clamping or crushing situation in which the operator's body part is trapped between a moving part of the robot system and another fixed or moving part of the work cell. In this situation, the pressure or force $\mathbf{F}_c$ of the robot system is applied for an extended period of time until the conditions are alleviated. The *transient* contact (i.e., dynamic impact, Fig. 12.7b) describes the contact between the moving part of the robot system and the operator's body part without clamping or trapping of that part. The actual contact is shorter than the aforementioned quasi-static contact ($<$50 ms), and depends on the inertia of the robot, the inertia of the operator's body part, and the relative speed $\mathbf{v}_c$ of the two.

The robot system must be adequately designed to reduce risk to an operator by not exceeding the applicable threshold limit values of force and pressure for quasi-static and transient contact. The limits can apply to forces, torques, velocities, momentum, mechanical power, joint ranges of motion, or space ranges. Threshold limit value for the relevant contact event on the exposed body region are determined for a worst-case scenario for both contact types.

The limit values presented in ISO/TS 15066:2016 are based on a conservative estimate and scientific research on pain sensations. Some informative values for

Table 12.3 Biomechanical limits for quasi-static contact

Body area	Maximum permissible pressure p_{QS}/N/cm^2	Maximum permissible force F_{QS}/N
Seventh neck muscle	210	150
Shoulder joint	160	210
Sternum	120	140
Abdomen	140	110
Pelvis	210	180
Humerus	220	150
Forearm	180	160
Palm	260	140
Forefinger pad	300	140
Forefinger end joint	280	140
Back of the hand	200	140
Thigh	250	220
Kneecap	220	220
Shin	220	130
Calf	210	130

maximum permissible pressure and maximum permissible force between the robot's part and operator's body region in quasi-static contact are presented in Table 12.3. Pressure and force values for transient contact (p_T, F_T) can be at least two times the values for quasi-static contact (p_{QS}, F_{QS}).

$$p_T = 2 \cdot p_{QS} \tag{12.2}$$
$$F_T = 2 \cdot F_{QS} \,. \tag{12.3}$$

Contact with face, skull, or forehead is not permissible and needs to be prevented.

For proper robot system reactions, both pressure and force limits must be taken into consideration, depending on the situation. In case of clamping of operator's body part (e.g., operator's hand), the resulting force can be well below the limit threshold so the pressure limit will be the limiting factor. On the other hand, if the contact is between two fairly large and soft areas (e.g., padded robot part and operator's abdomen), the resulting pressure will be below the limit threshold and the limiting factor will then be the force limit.

In case of contact, the robot system must react in a way that the effect of the identified contact remains below the identified threshold limit values, as presented in Fig. 12.8. In case of clamping or pinning a body part between a robot segment and some other object, the robot must limit the speed to comply with the protective limits. The robot should also have an integrated option for the operator to manually extricate the affected body area.

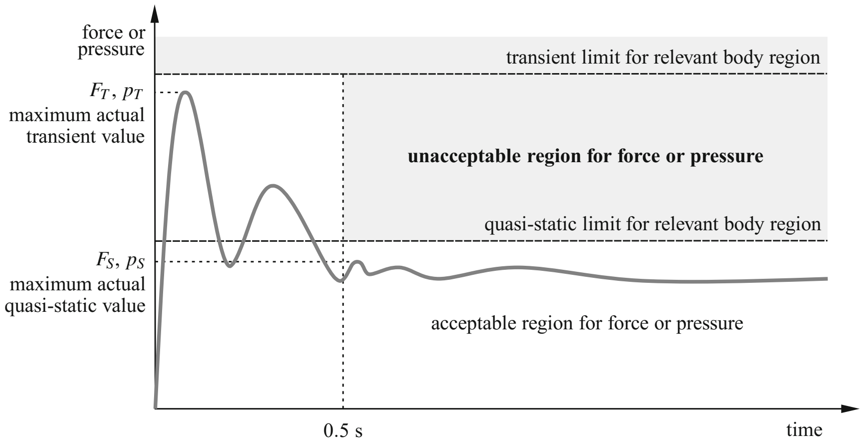

Fig. 12.8 Graphical representation of the acceptable and unacceptable forces or pressures in case of quasi-static or transient contact

The power and force limiting method can be used in collaborative application where the presence of the operator is frequently needed, in time-dependant operations (where delay due to safety-rated stops is unwanted but physical contact between the robot system and the operator can occur), and applications with small parts and high variability of assembly.

12.4 Collaborative Robot Grippers

The design and control of a collaborative robot enables the robot to be safe while working together with the operator. But the robot itself is just a part of the robot system. Grippers represent an important part of the robot system as they are used for object manipulation in the direct vicinity of the operator. As such, grippers must attain high level of safety.

The grippers are usually rigidly attached to the already-safe robot with built-in speed and force limitations. The shape and materials of the gripper must coincide with the safety design preventing exceeded pressure limits on the contact area of the operator's body. In addition, the grippers at the tip of the robot should create as little inertia as possible to minimally interfere with robot's safety features.

The design of the grippers should prevent the operator from getting their fingers stuck in the gripper or in the connecting cables. The grippers must have implemented a safe mode under an emergency stop, which function depends on the application. If there is a gripped part, the operator usually wants the part to stay safely gripped. When teaching and closing the gripper, the operator wants the gripper to stop applying the force.

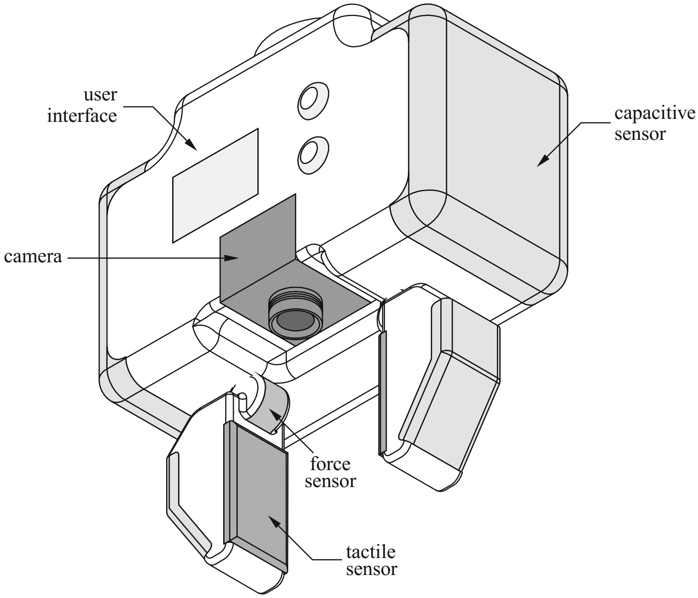

Fig. 12.9 Conceptual design of a gripper for collaborative gripping

When the gripper is interacting with the part, the operator wants a good solid grip. The grip also has to be secure under an emergency stop or power loss as a dropped part could represent a danger for an operator, robot, or environment. If the robot is moving fast, the dropped part could become a projectile.

Grippers can be equipped with different sensors to increase the operator's safety (Fig. 12.9). Capacitive sensors are used for early operator detection and thus prevention of unwanted contacts. Camera systems can detect the robot's surroundings and aids in object search. Tactile sensors are used to differentiate between workpiece and operator. To set adequate gripping force, different force sensors can be integrated. The gripper design can also include different user interfaces, such as LCD screen, signal lights, and control buttons.

Grippers used in the collaborative robot systems should be easy to install and program. The future design of the grippers is tending away from user programming towards grippers that will be capable of automatic adaptation depending of the parts and applications.

12.5 Applications of Collaborative Robotic System

The document ISO 10218-2:2011 provides the division of collaborative applications into five categories presented in Fig. 12.10.

Hand-over window application (see Fig. 12.10a) covers loading/unloading, testing, benching, cleaning, and service tasks. The robot is positioned behind fixed or

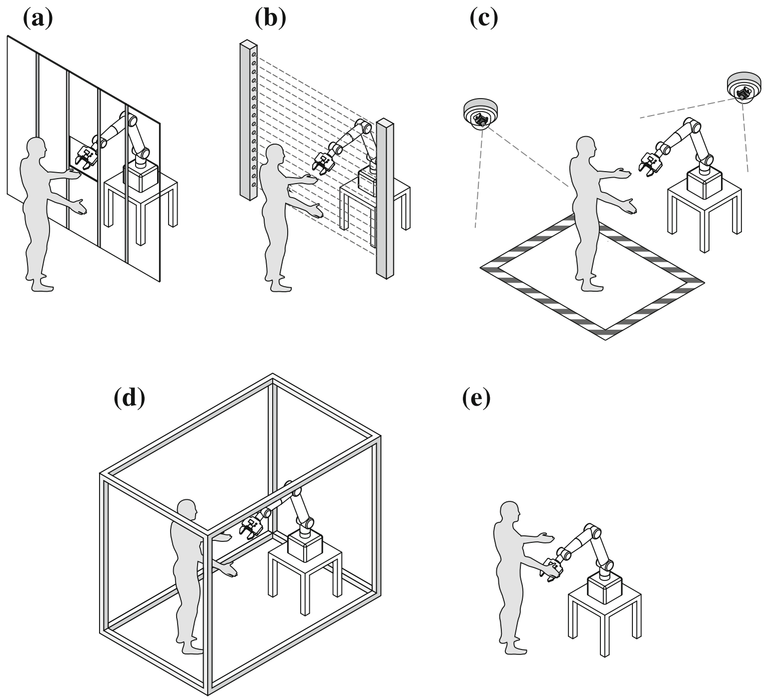

Fig. 12.10 Conceptual applications of collaborative robots: **a** hand-over window, **b** interface window, **c** collaborative workspace, **d** inspection, and **e** hand-guided robot (ISO 10218-2:2011)

sensitive guards around the workspace where the application is performed in automatic mode without limitations. Interaction with the operator is performed through a window. In the vicinity of the window the robot reduces its speed. The window also acts as the limit for the robot workspace.

The interface window (Fig. 12.10b) acts as a barrier for the robot system. On the robot side the robot can perform autonomous automatic operations. The robot system is also guarded by fixed or sensitive guards around the workspace. The robot stops at the interface window and can be then manually moved outside the interface. For guided movement the robot must be equipped with hand guiding device. This method is used for automatic stacking, guided assembly, guided filling, testing, benching, and cleaning.

Applications including simple assembling and handling can take advantages of the collaborative workspace (Fig. 12.10c). Inside the common workspace the robot can perform automatic operations. When the operator enters the collaborative workspace, the robot reduces speed and/or stops. In this type of application, additional person-detection systems using one or more sensors are needed.

Applications including inspection and parameters tuning (e.g., welding application, see Fig. 12.10d) require guarded workspace and person-detection systems.

When the operator enters the shared workspace, the robot continues operation with reduced speed. The application needs to have additional measures to prevent misuse.

Hand-guided robots (Fig. 12.10e) are used for hand-guided applications (e.g., assembling or painting). The robot is equipped with hand-guiding device. The operator guides the robot by hand along a path in a task-specific workspace with reduced speed. The area of collaborative workspace is mainly dependent on the hazards of the required application.