By 2007, the evolution of industrial robots was marked by the following main trends [42.15]:

- The average robot unit price fell to about one-third of its equivalent price in 1990, which meant that automation is becoming more affordable. At the same time, robot performance parameters such as speed, load capacity, and mean time between failures (MTBF) have dramatically improved. These improvements provide a faster return on investment, particularly for small, short-run batch production.
- Off-the-shelf components from personal computer (PC) technologies, consumer software, and the IT industry have contributed to improved performance-to-cost ratios. Today, most manufacturers integrate PC-based processors in their controllers as well as software for programming, communication, simulation, and maintenance from high-volume IT-markets.
- Multiple robots can be programmed and synchronized in real time by one controller, which allows robots to cooperate precisely on a single workpiece.
- Increasingly, vision systems for object identification, localization, and quality control have become an integral part of the robot controller.
- Robots are networked by fieldbuses or ethernet for control, configuration, and maintenance.
- New financing arrangements allow end-users to rent a robot or even have a robot workcell operated by a specialized company or even the robot supplier in order to reduce risks or to save on investment capital.
- Training and education have become important services to end-users to increase acceptance of robot technology. Specific multimedia material and courses aim at educating industrial engineers and workforce to effectively plan, program, operate, and maintain industrial robot workcells.

42.2 Typical Applications and Robot Configurations

42.2.1 Welding

Welding ranks among the most important joining processes in manufacturing. Manual welding requires highly skilled workers, as small imperfections in the weld can lead to severe consequences. Why is a robot suited to perform this critical job? Modern welding robots have the following characteristics:

- Computer control allows the programming of task sequences, robot motions, external actuators, sensors, and communication with external devices.
- Free definition and parameterization of robot positions/orientations, reference frames, and trajectories.
- High repeatability and positioning accuracy of trajectories. Typically repeatability is some ± 0.1 mm and positioning accuracy is of the order of ± 1.0 mm.
- High speeds of the end-effector of up to 8 m/s.
- Typically, articulated robots have six DOF so that commanded orientations and positions in their workspace can be reached. Workspace extensions by mounting the robot on a linear axis (seventh DOF) are common, especially for welding of large structures.
- Typical payloads of 6–100 kg.
- Advanced programmable logic controller (PLC) capabilities such as fast input/output control and synchronizing actions within the robot workcell.
- Interfacing to high-level factory control through fieldbuses or ethernet.

Metal inert/active gas (MIG/MAG) welding is the predominant application of industrial robotics today. The automatic arc-welding process is based on a consumable wire electrode and a shielding gas that are fed through a welding gun (Fig. 42.8). Electric current sources, torches, and peripheral devices for automatic cleaning and maintaining the torch (anti-splatter, wire-cutting, tool changer etc.) are offered by specialized companies. Often sensors are used to track welding gaps and measure weld seams either before or synchronously to the welding process, thus adapting the robot's trajectory in the presence of workpiece variation and distortion. Also, cooperating robots have been introduced where one robot fixes and moves the workpiece in synchronization with another robot carrying a welding tool so that the weld can be performed with the pool of molten metal horizontal.

Another interesting robot task is multilayer welding. In regular intervals the robot measures the profile of the weld gap and adaptively generates subsequent tool paths to apply successive weld seams until the final required geometry is reached. In the example shown in Fig. 42.8c up to 70 seams can be produced by the robot to weld thick metal plates.

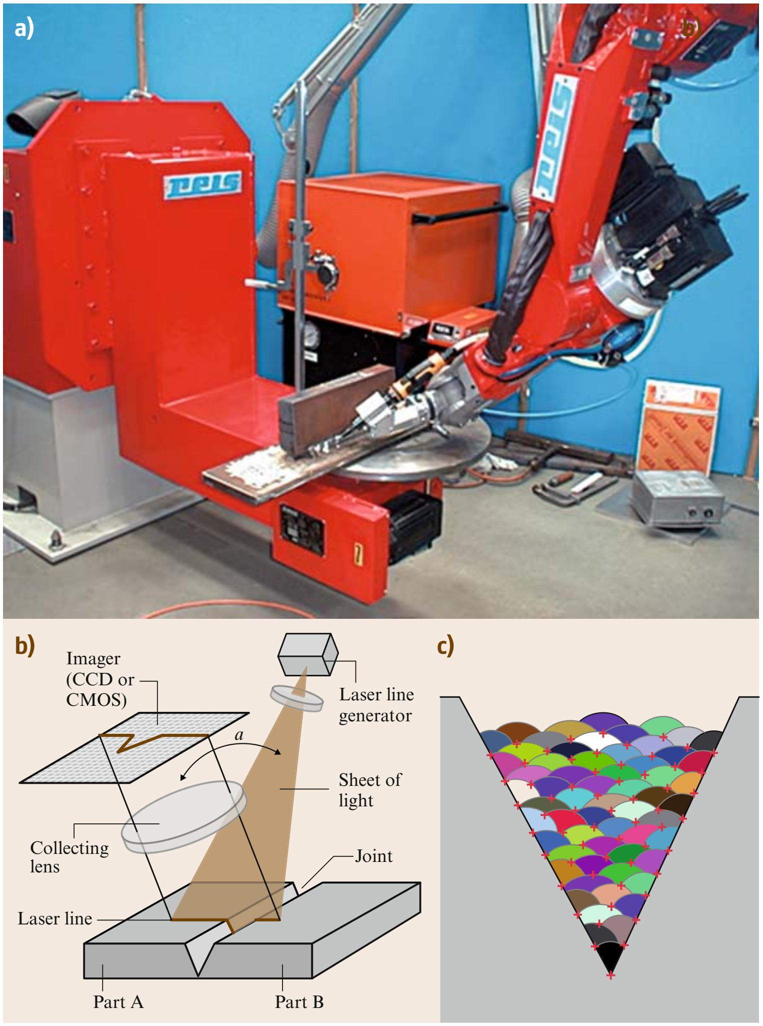

Fig. 42.8a–c Robot welding with sensor guidance. **(a)** The welding robot workcell consists of a 6 DOF robot, a turning table so that the seam is accessible and welded in a flat position, the weld source with a fume extractor and the welding torch. Safety fences and light shields are not shown. The welding torch is attached to the robot flange. A service station (not shown) in the robot workcell is approached regularly to clean the gas nozzle. **(b)** A typical weld seam sensor is based on the so-called laser triangulation principle. The sensor is attached to the robot and a laser projects a sharp stripe on the seam. The stripe is detected by an imager, typically a 2-D CCD camera. From the extracted contour the position of the seam relative to the sensor is calculated. **(c)** Multiple seams can be generated based on this information

42.2.2 Car Body Assembly

Early on, car body assembly became the predominant robot application as the benefit for robot automation was apparent. Handling and positioning the metal sheets, spot welding, and transport of the body frames was either hazardous, physically demanding to the worker, or difficult to realize on fixed automation lines given the desired variety of car body configurations to be assembled on the one production line (Fig. 42.9). In the stamping section metal sheets are cut into plates (or *blanks*) ready for pressing into body panels. In subsequent steps robots load the panels onto a tray that fixes the panels for other robots to be spot-welded. After inspection the finished bodies are transferred by conveyor to the paint shop.

Individual assembly units and components such as motors, transmissions, axles, doors or fenders are premounted in separate areas. The car body is delivered to the body assembly area *just in sequence*, i. e. at the right time and place on the assembly line. The climax of the assembly process(wedding) – when the engine, drive and chassis first meet takes place before the last parts are monted on the car.

Today's industrial robots, particularly in the workload category of 100–300 kg, are to a large extent the results of the requirements stemming from this application:

- Required repeatability of at least ± 0.5 mm under typical loads of some 100 kg for the spot-welding

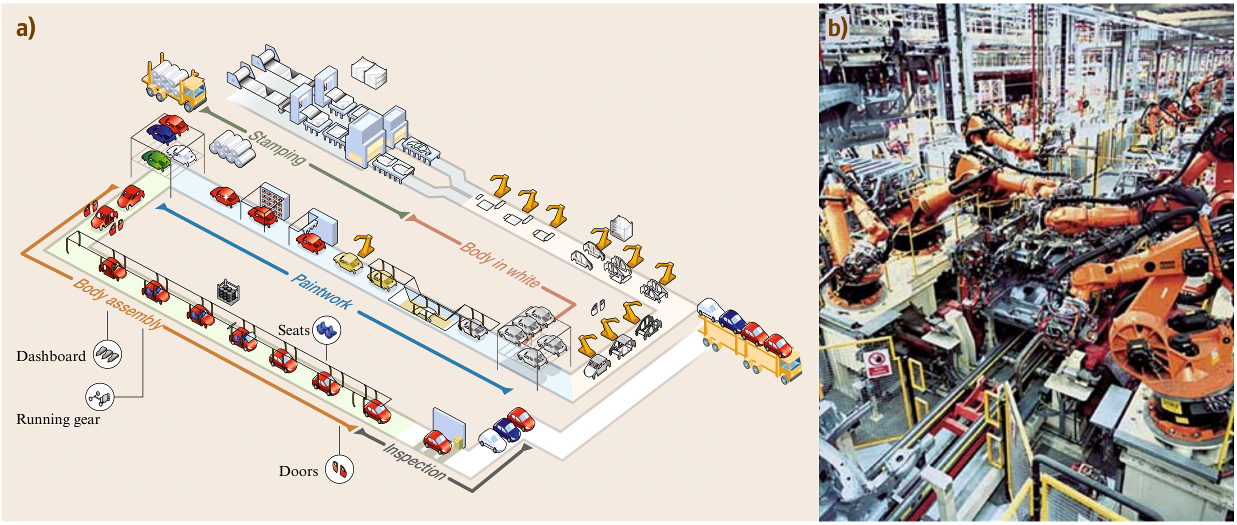

Fig. 42.9a,b Car body assembly. **(a)** A car body assembly usually follows the illustrated steps: Stamping of the metal sheet into plates, fixing and alignment of the plates on trays, spot welding, painting the car body, and final assembly of the car body (doors, dashboard, windscreens, power-train seats, and tires). Car factories can host well over 1000 robots working two to three shifts per day. (Courtesy PSA Peugeot Citroën, Paris and Art Movies, Paris) **(b)** The Mercedes A class assembly in Rastatt Germany is highly automated. The picture shows spot welding robots along the, *body in white* transfer line. Trays carrying car bodies pass through the *robot garden*

tool and cable package leads to stiff and heavy arm structures. A typical robot weight-to-payload ratio is of the order of 1500 kg:150 kg.

- Three-shift continuous operation requires highest reliability of both robot and equipment. Typical mean time between failure (MTBF) is reported to be around than 50 000 h [42.1].
- The line capacity depends on the robot's speed to place spot welds. Thus, the *point-to-point* (PTP) movement time between welding positions should be kept as short as possible. This is mainly achieved by powerful drives so that the mean power consumption of the robot drives is typically 5 kW.
- Most of the trajectories, positions, and orientations are generated using *offline programming* (OLP) systems. Accurate simulations of the robot motion depend on robot models, which incorporate both robot kinematic properties and controller characteristics. The *realistic robot simulation* (RSS) interface is the accepted standard format for robot models of offline programming systems [42.16].

42.2.3 Painting

Hazardous working conditions for human operators motivated Trallfa, a Norwegian company, to develop simple spray-painting robots in 1969, particularly for spraying bumpers and other plastic parts in the automotive industry. Initially pneumatically driven for antiexplosion reasons, today's robot designs are fully electric with greatly improved spray guns. They also have hooks and grippers to open hoods and doors during the painting task. Hollow wrists that house gas and paint hoses allow fast and agile motions. Spray guns for robots have evolved dramatically for delivering uniform quality using as little paint and solvent as possible and also for switching between different paint colors. Originally spray-painting robots replicated movements copied from human workers. Most of the programming for robot painting today is done offline as state-of-the-art programming systems offer integrated process simulations to optimize paint deposition, thickness, and coverage (Fig. 42.10).

42.2.4 Material Transfer Automation

Generally, industrial practice in robot workcell planning aims at finding a compromise between reducing the variation of the workpiece position and the cost of sensor systems to compensate for residual variation. Nearly all parts arrive at robot workcells in a repeatable manner, either being stored in special magazines, or by being

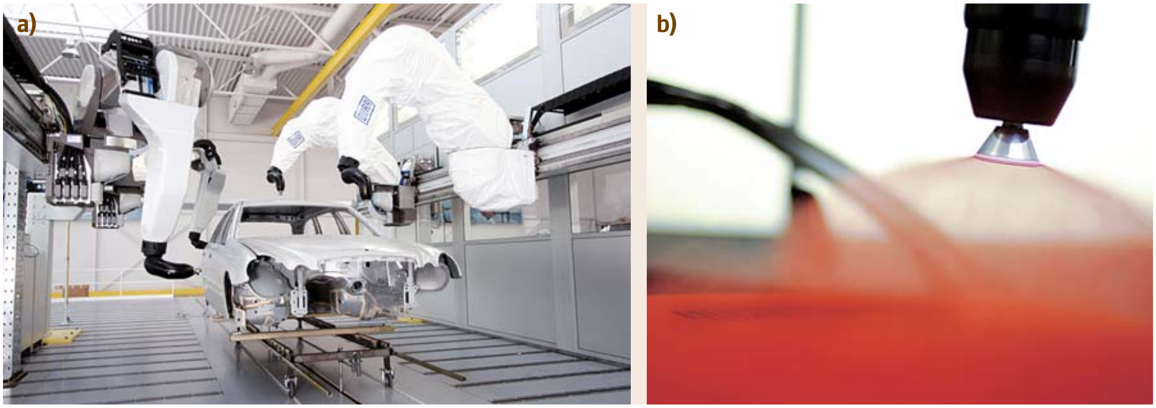

Fig. 42.10a,b Painting robots. **(a)** A multi-robot workcell for car body painting **(b)** High-speed rotating atomizer and charge. Painting robots. **(a)** are used for surface coating of car bodies and other parts. All current paint materials such as solvent-based paints, water-borne paints and powder can be applied. In car production, multiple robots work in parallel for optimal throughput and accessibility of the car body. Most of the programming which includes the synchronisation of the robots is performed offline. Paint guns are critical to the process quality. Figure **(b)** shows a Dürr EcoBell2 paint gun which atomizes the paint material at the edge of the rotating bell disk by centrifugal forces (by courtesy Dürr, Stuttgart)

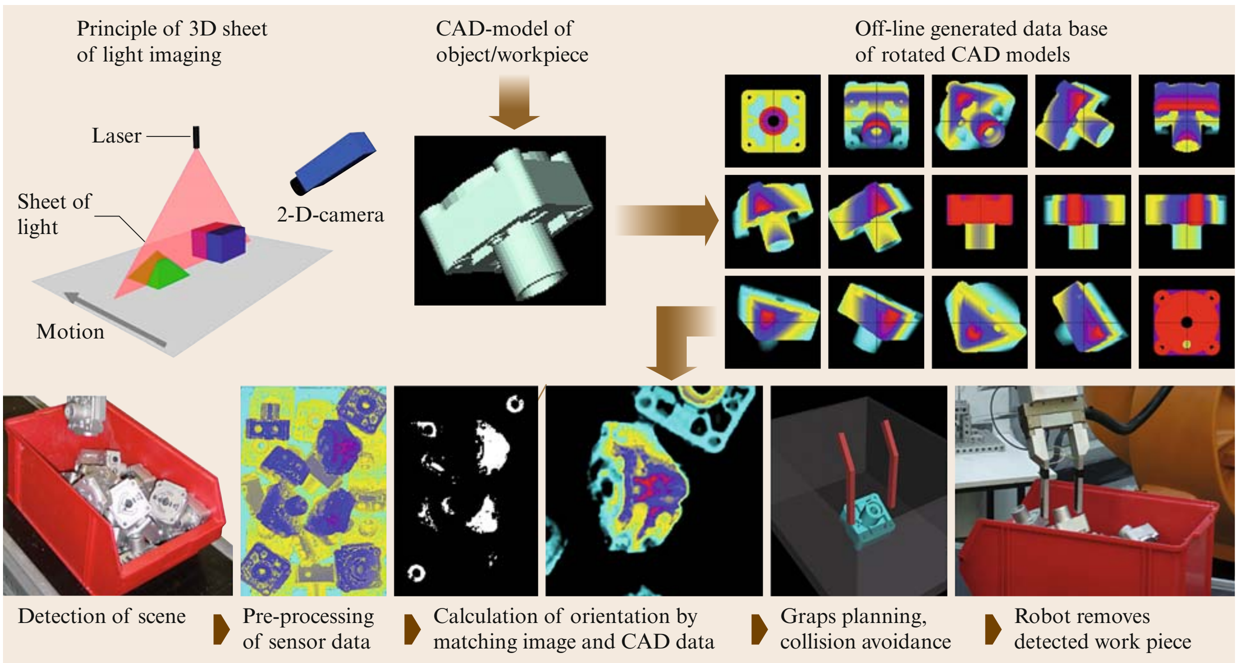

Fig. 42.11 Robot bin picking. A scene containing the objects is acquired by a 3-D sensor e.g. based on the laser triangulation principle. Beforehand this approach turns the CAD object virtually in discrete spatial angles in an off-line calculation. Feature histograms for each view are generated and stored in a database. A best match between actual feature histograms and the simulated sets of histograms determines the location of the object. A grasp has to be selected and a collision-free trajectory is generated. A typical cycle time of a location process is between 1 and 2 s

transported by vibrating devices that allow the parts to settle into a predictable orientation.

If randomly oriented in a carrier or a box, parts have to be properly located so that the robot can grasp them appropriately. This challenge in industrial robotics has been referred to as *bin-picking* and has been investigated by numerous researchers since the mid-1980s [42.17]. Even though an abundance of approaches has been presented a cost-effective standard solution has not been established yet [42.18].

Barely 10% of industrial robot installations in 2006 were sensor-equipped. However, it is expected that many future robots will have standard embedded force-torque and vision sensors. This is a precondition for advanced vision for object identification and localization in manufacturing.

One method for determining random object locations using the object's computer-aided design (CAD) data starts with point clouds of a scene acquired by a three-dimensional (3-D) sensor (Fig. 42.11). A selection of 3-D sensors is described in Chap. 22. The CAD model has been virtually turned into discrete spatial angles in an offline calculation. Feature histograms for each view are generated and stored in a database with

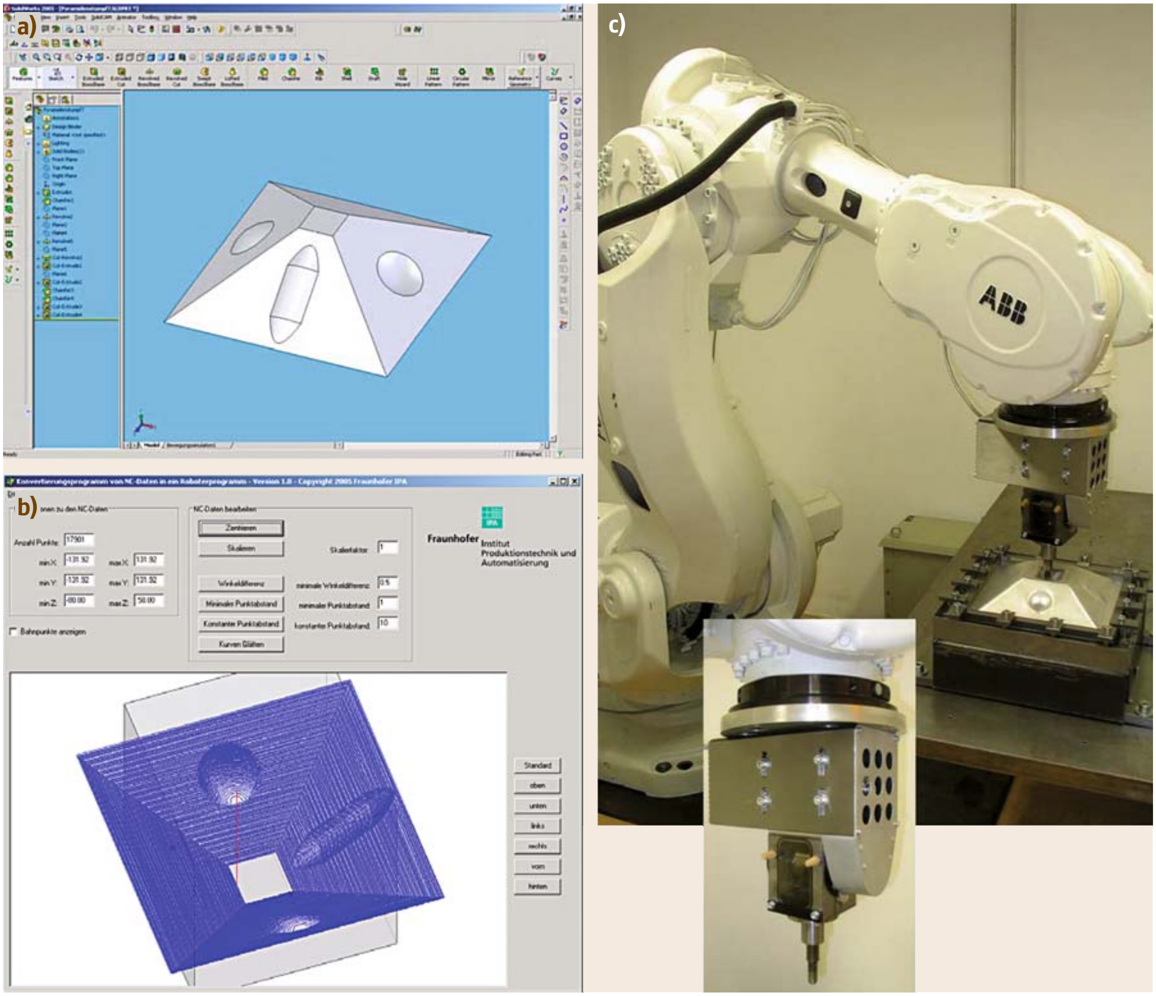

Fig. 42.12a–c Trajectory generation for incremental machining processes. In this example, the forming process of metal sheets is based on an oscillating stamp (amplitude 1 mm, 50 Hz frequency) which locally plastifies the metal in incremental steps. From the CAD model **(a)**, the robot's trajectories are calculated offline on the basis of specific material models **(b)**. Each line represents a part of the tool trajectory. **(c)** Shows a demonstrator robot workcell with the tool in detail

the given angular information (typically in 10° steps for all spatial angles).

A best-match process compares actual feature histograms with the simulated sets of histograms in the database. For the determined location of the object, a grasp has to be selected and a collision-free trajectory be generated. The latter steps can be quite critical as residual workpieces at the box bottom may constrain the robot's grasp and departing trajectory [42.19].

42.2.5 Machining

Compared to a milling machine or a lathe, standard robots possess much less stiffness (by a factor of 20–50 times), but much greater dexterity. A serial robot's stiffness is usually very anisotropic throughout its working space and may vary for a typical heavy duty model in the range 200–700 N/mm. Therefore, robots can machine workpieces (grinding, fettling, polishing etc.) provided that tool forces can be reduced to acceptable values for a given robot manipulator. This incremental approach to machining, particularly for cutting and forming, can produce good results. However, these sequential robot motions have to be generated automatically, which requires merging the process information with the workpiece geometry.

An example of a novel process that benefits from the robot's versatility in terms of programming, dexterity, and cost is the so-called incremental forming process of metal sheets. Without using any costly form, metal sheets are clamped in a rigid frame and the robot produces a given 3-D contour by guiding a tool equipped with a high-frequency oscillating stamp (amplitude typically 1 mm at a frequency of 50 Hz) over the metal surface. The robot's trajectories are calculated from the CAD model on the basis of specific material models. The robot's program is generated and passed to the controller. One-off housings for machines, prototype panels or customized car panels can be economically produced using this method [42.20]. Figure 42.12 depicts the sequence of actions for automatically generating and executing the forming program.

42.2.6 Human–Robot Cooperation for Handling Tasks

Robots for human augmentation (force or precision augmentation) stretch from fully automated operation to acting as a servo-controlled balancer (see also Chap. 57). As an example: in a car drive train assembly the heavy gear box is grasped by the robot which balances it softly so the worker can insert it precisely into the housing (Fig. 42.13). Preprogrammed virtual walls give the worker a realistic feeling of constraints.

The central interface for the worker's tactile commands is a handle equipped with safety switches. These switches trigger the force-torque sensor that is attached to the robot's flange. Upon touching both safety switches (two-handed operation) the force-torque sensor is activated and the robot control is set to a safe

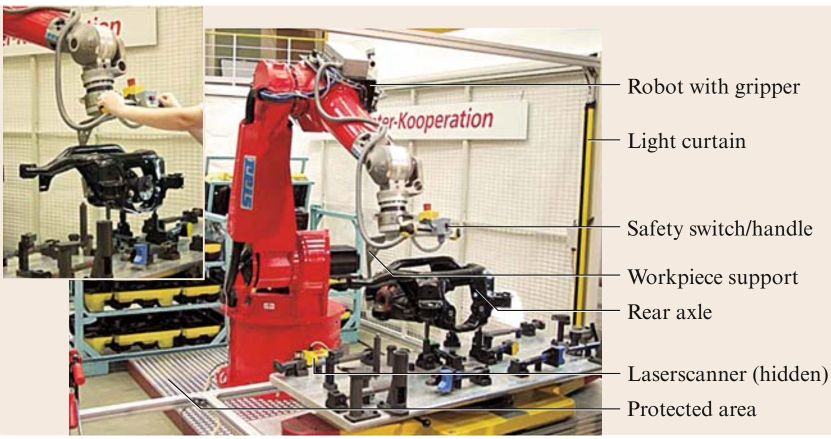

Fig. 42.13 Human-robot-cooperation for handling tasks. Inside a regular workcell which is secured by light curtains, the robot handles gear boxes at regular speed in fully automated mode. Upon approaching the light curtain at reduced speed, the worker grasps the safety switch which activates both the reduced-speed mode and the force-torque sensor. The worker guides the robot almost effortlessly by its handle so that the gear-box is balanced with precision into the rear axle frame for final assembly (Fraunhofer IPA, Stuttgart)

reduced end-effector speed (of some 50 mm/s). Thus, the sensor scales the applied force/torque information into a compliant robot motion. Obviously the physical human–robot cooperation has to obey safety precautions as the robot's and worker's workspaces overlap.

The ISO 10218-1:2006 standard specifies requirements and guidelines for the inherent safe design, protective measures, and information for use of industrial robots. It describes basic hazards associated with robots, and provides requirements to eliminate or adequately reduce the risks associated with these hazards. A novel element of this revised standard is the regulation of so-called collaborative operation, where the robot works in direct cooperation with a human within a defined workspace. Basically the collaborative operation depends on several criteria, which have to be met by the robot workcell [42.21]:

1. The hand-guiding equipment shall be located in the area of the end-effector.
2. The robot moves with safe reduced speed (less than 250 mm/s) and safe monitored position. This position monitoring shall be according to at least category 3 of ISO 13849, unless a risk assessment is performed and determines that a higher category is required [42.22, 23].
3. The robot must sense and keep a safe distance from the human. The distance relates to the attended speed. The distance and speed monitoring shall be according to at least category 3 of ISO 13849, unless a risk assessment is performed and determines that another category is required.

If a robot's total power consumption can safely be limited to 80 W as well as its static impact forces to 150 N no additional sensor-based safety precautions are needed. Again, these conditions have to be secured by a risk assessment or security systems which comply with at least category 3 of ISO 13849 [42.21]. Currently, novel control algorithms, kinematic and actuator designs are being investigated to realize so-called intrinsically safe robots [42.24].

The described workcell complies with the ISO standard in such a way that the presence of the human is detected by activating both safety switches of the handle (first condition). The robot's built-in safe controller safely measures the end-effector's position and limits its velocity [42.25] (second condition). Meanwhile most of the robot manufactures provide safe category 3 controllers. If the worker's presence in the workspace is not known (third condition, not applicable here) a safe sensor system has to detect safely the workers location according to category 3. Three-dimensional sensors meeting category 3 first appeared on the market in 2006, thus opening up a wide field of potential collaborative operations [42.26].

42.3 Kinematics and Mechanisms

The choice of mechanism, its kinematic properties, the computation methods used to determine joint motions, and the intended application of a robot manipulator are all closely related. The diagrams in Table 42.1 show several common types of robot mechanism.

With advances in the state of the art in kinematic algorithms and computer hardware processing capabilities, computation is much less of a constraint on mechanism choice than it was for early robot designers. The choice of mechanical structure of the robot depends mostly on fundamental mechanical requirements such as payload and workspace size. Considering a given level of cost, there is usually a tradeoff between workspace size and stiffness. To enable the robot to reach inside or around obstacles it is clearly advantageous to use an articulated mechanical design.

Considering also the stiffness and accuracy (in a practical sense considering what is reasonable to build), the picture is more complex. Each of the first three types in Table 42.1 we refer to as *serial kinematic machines* (SKMs), while the last is a *parallel kinematic machine* (PKM). To obtain maximum stiffness, again for a certain minimum level of cost, the end-effector is better supported from different directions, and here the PKM has significant advantages. On the other hand, if high stiffness (but not low weight and high dexterity) is the main concern, a typical computerized numerical control (CNC) machine (e.g., for milling) is identical in principle to the gantry mechanism. There are also modular systems with servo-controlled actuators that can be used to build both robots with purpose-designed mechanisms.