28

Present State and Future Trends in Mechanical Systems Design for Robot Application

Martin Hägele
Fraunhofer Institute

Rolf Dieter Schraft
Fraunhofer Institute

28.1 Introduction

In 1999 some 940,000 industrial robots were at work and major industrial countries reported growth rates in robot installation of more than 20% compared to the previous year (see Figure 28.1) The automotive, electric, and electronic industries have been the largest robot users; the predominant applications are welding, assembly, material handling, and dispensing. The flexibility and versatility of industrial robot technology have been strongly driven by the needs of these industries, which account for more than 75% of the world's installation numbers. Still, the motor vehicle industry accounts for some 50% of the total robot investment worldwide.[9]

Robots are now mature products facing enormous competition by international manufacturers and falling unit costs. A complete six-axis robot with a load capacity of 10 kg was offered at less than $60,000 in 1999. It should be noted that the unit price only accounts for about 30% of the total system cost. However, for many standard applications in welding, assembly, palletizing, and packaging, preconfigured, highly flexible workcells are offered by robot manufacturers, thus providing cost effective automation to small and medium sized operations.

A broad spectrum of routine job functions led to a robotics renaissance and the appearance of service robots. Modern information and telecommunication technologies have had a tremendous impact on exploiting productivity and profitability potentials in administrative, communicative, and consultative services. Many transportation, handling, and machining tasks are now automated. Examples of diverse application fields for robots include cleaning, inspection, disaster control, waste sorting, and transportation of goods in offices or hospitals. It is widely accepted that service robots can contribute significantly to better working conditions, improved quality, profitability, and availability of services. Statistics on the use and distribution of service robots are scarce and incomplete. Based on sales figures from leading manufacturers, the total service robot stock can

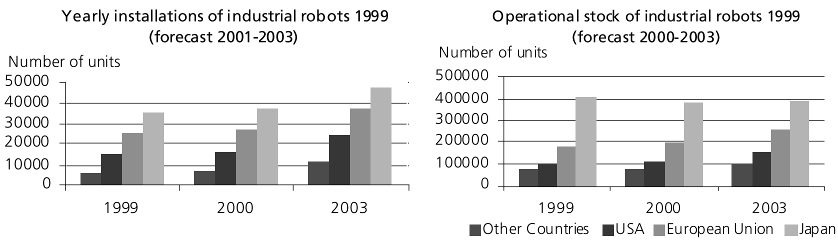


FIGURE 28.1 Yearly installations and operational stock of industrial robots worldwide.

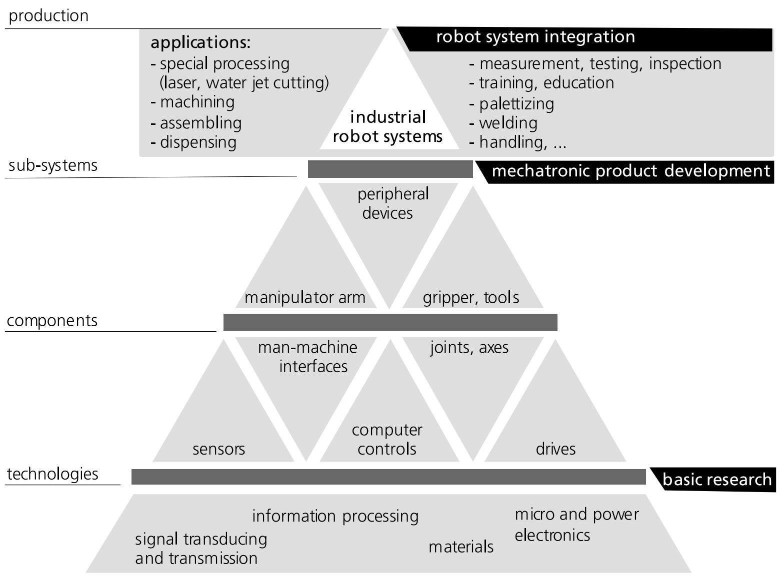


FIGURE 28.2 Robotics and mechatronics. (From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)

be estimated at a few thousand and certainly below 10,000 units. It is expected that within ten years, service robots may become commodities and surpass industrial robot applications.

Robots are representative of mechatronics devices which integrate aspects of manipulation, sensing, control, and communication. Rarely have so many technologies and scientific disciplines focused on the functionality and performance of a system as they have done in the fields of robot development and application. Robotics integrates the states of the art of many front-running technologies as depicted in Figure 28.2.

This chapter will give an overview of the state of the art and current trends in robot design and application. Industrial and service robots will be considered and typical examples of their system design will be presented in two case studies.

28.2 Industrial Robots

28.2.1 Definition and Applications of Industrial Robots

Large efforts have been made to define an industrial robot and to classify its application by industrial branches so that remarkably precise data and monitoring are available today.[9] According to ISO 8373, a manipulating industrial robot is defined as:

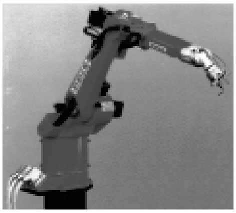
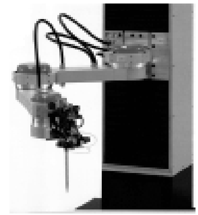
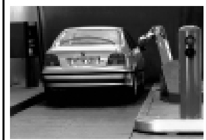
Specialization of robots			
universal robot	application specific	specialist (modular design)	specialist (customized design)
			
Examples: Reis RV6	ABB Flex Palettizer	CMB Modular Robot	IPA Robot Refuelling
• design fits standard applications • product variants according to payload, dexterity, working envelope • use of customized components • high manufacturing quantities	• application-oriented designs • integrated process-control functions • preconfigured workcells available • medium manufacturing quantities	• task specific design • integration of standard modules (axis, control, sensors) • preferred applications: material handling • small manufacturing quantities	• task specific designs • primary applications: nonmanufacturing fields (service robots) • task based kinematic structure • small to large manufacturing quantities

FIGURE 28.3 Examples of specialization of robot designs. (Courtesy of Reis Robotics, ABB Flexible Automation, and CMB Automation. From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)

> An automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes (in three or more degrees of freedom, DOF), which may be either fixed in place or mobile for use in industrial automation applications.

The terms used in the definition above are:

- Reprogrammable: a device whose programmed motions or auxiliary functions may be changed without physical alterations.
- Multipurpose: capable of being adapted to a different application with physical alterations.
- Physical alterations: alterations of the mechanical structure or control system except for changing programming cassettes, ROMs, etc.
- Axis: direction used to specify motion in a linear or rotary mode.

A large variety of robot designs evolved from specific task requirements (see Figure 28.3). The specialization of robot designs had a direct impact on robot specifications and its general appearance. The number of multipurpose or universal robot designs was overwhelming. However, many applications are common enough that robot designs with specific process requirements emerged. Examples of the different designs and their specific requirements are shown in Figure 28.4.

28.2.2 Robot Kinematic Design

The task of an industrial robot in general is to move a body (workpiece or tool) with six maximal Cartesian spatial DOF (three translations, three rotations) to another point and orientation within a workspace. The complexity of the task determines the required kinematic configuration. The number of DOFs determines how many independently driven and controlled axes are needed to move a body in a defined way. In the kinematic description of a robot, we distinguish between:

- Arm: an interconnected set of links and powered joints that support or move a wrist, a hand or an end effector.
- Wrist: a set of joints between the arm and the hand that allows the hand to be oriented to the workpiece. The wrist is for orientation and small changes in position.

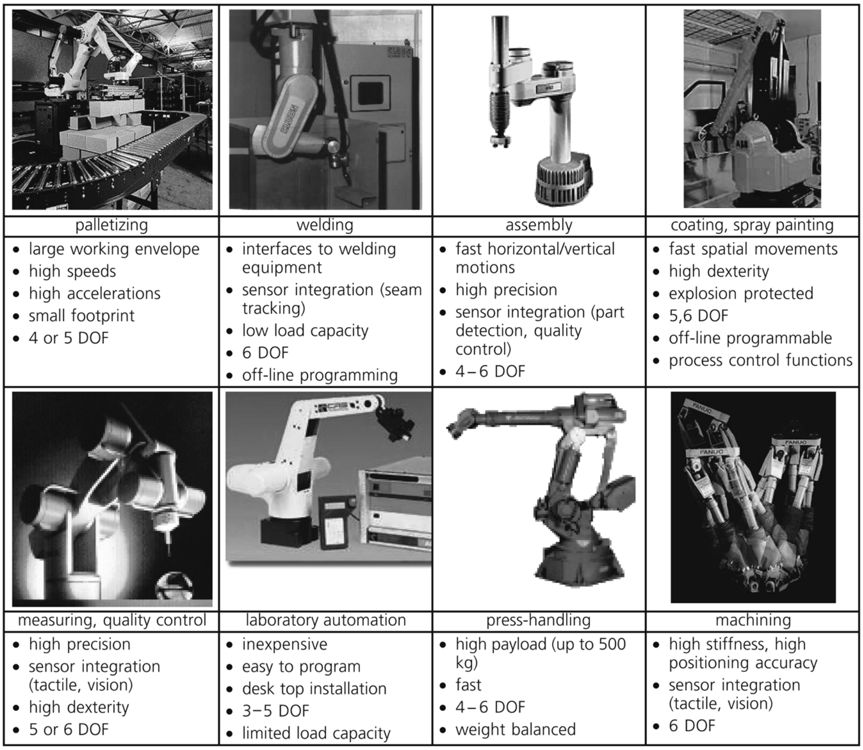


FIGURE 28.4 Application-specific designs of robots and their major functional requirements. (Courtesy of FANUC Robotics, CLOOS, Adept Technology, ABB Flexible Automation, Jenoptik, CRC Robotics, and Motoman Robotec. From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)

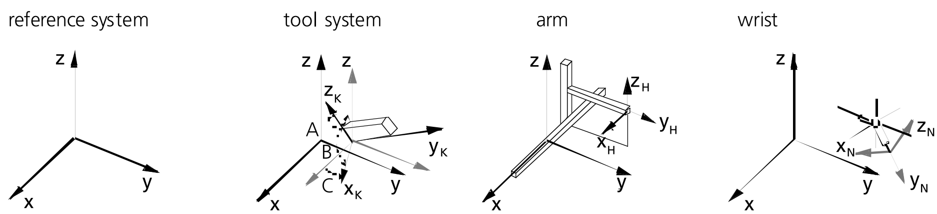


FIGURE 28.5 Definition of coordinate systems for the handling task and the robot.

Figure 28.5 illustrates the following definitions:

- The reference system defines the base of the robot and, also in most cases, the zero position of the axes and the wrist.
- The tools system describes the position of a work piece or tool with six DOFs (X_k, Y_k, Z_k, A, B, C).
- The robot (arm and wrist) is the link between the reference and tool systems.

Axes are distinguished as follows:

- Rotary axis: an assembly connecting two rigid members that enables one to rotate in relation to the other around a fixed axis.
- Translatory axis: an assembly between two rigid members enabling one to have linear motion in contact with the other.

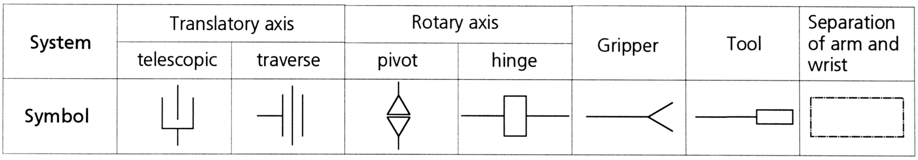


FIGURE 28.6 Symbols for the kinematic structure description of industrial robots according to VDI guideline 2681.

Figure 28.6 shows an overview of the symbols used in VDI guideline 2861 and in this chapter. Any kinematic chain can be combined by translatory and rotatory axes.

The manifold of possible variations of an industrial robot structure can be determined as follows:

$$V = 6^{DOF}$$

where V = number of variations and DOF = number of degrees of freedom. A large number of different chains can be built; for example, 46,656 different kinematic chains are possible for six axes. However, a large number is inappropriate for kinematic reasons:[1]

- Positioning accuracy generally decreases with the number of axes.
- Kinetostatic performance depends directly on the choice of kinematic configuration and its link and joint parameters.
- Power transmission becomes more difficult as the number of axes increases.

Industrial robots normally have up to four principal arm axes and three wrist axes. Figure 28.7 shows the most important kinematic chains. While many existing robot structures use serial kinematic chains (with the exception of closed chains for weight compensation and motion transmission), some parallel kinematic structures have been adopted for a variety of tasks. Most closed-loop kinematics are based on the so-called hexapod principle (Steward platform), which represents a mechanically simple and efficient design. The structure is stiff and allows excellent positioning accuracy and high speeds, but working volume is limited.

If the number of independent robot axes (arm and wrist) is greater than six, we speak of kinematically redundant arms. Because there are more joints than the minimum number required, internal motions may allow the manipulator to move while keeping the position of the end effector fixed.[14] The improved kinematic dexterity may be useful for tasks taking place under severe kinematic constraints. Redundant configuration such as a six-axis articulate robot installed on a linear axis (Figure 28.8) or even a mobile robot (automated guided vehicle, AGV) is quite common and used as a measure to increase the working volume of a robot.

28.2.2.1 Cartesian Robots

Cartesian robots have three prismatic joints whose axes are coincident with a Cartesian coordinate system. Most Cartesian robots come as gantries, which are distinguished by framed structures supporting linear axes. Gantry robots are widely used for handling tasks such as palletizing, warehousing, order picking, and special machining tasks such as water jet or laser cutting where robot motions cover large surfaces.

Most gantry robot designs follow a modular system. Their axes can be arranged and dimensioned according to the given tasks. Wrists can be attached to the gantry's z axis for end effector orientation (Figure 28.9). A large variety of linear axes can be combined. Numerous component manufacturers offer complete programs of different sized axes, drives, computer controls cable carriers, grippers, etc.

28.2.2.2 Cylindrical and Spherical Robots

Cylindrical and spherical robots have two rotary and one prismatic joint. A cylindrical robot's arm forms a cylindrical coordinate system, and a spherical robot arm forms a spherical coordinate

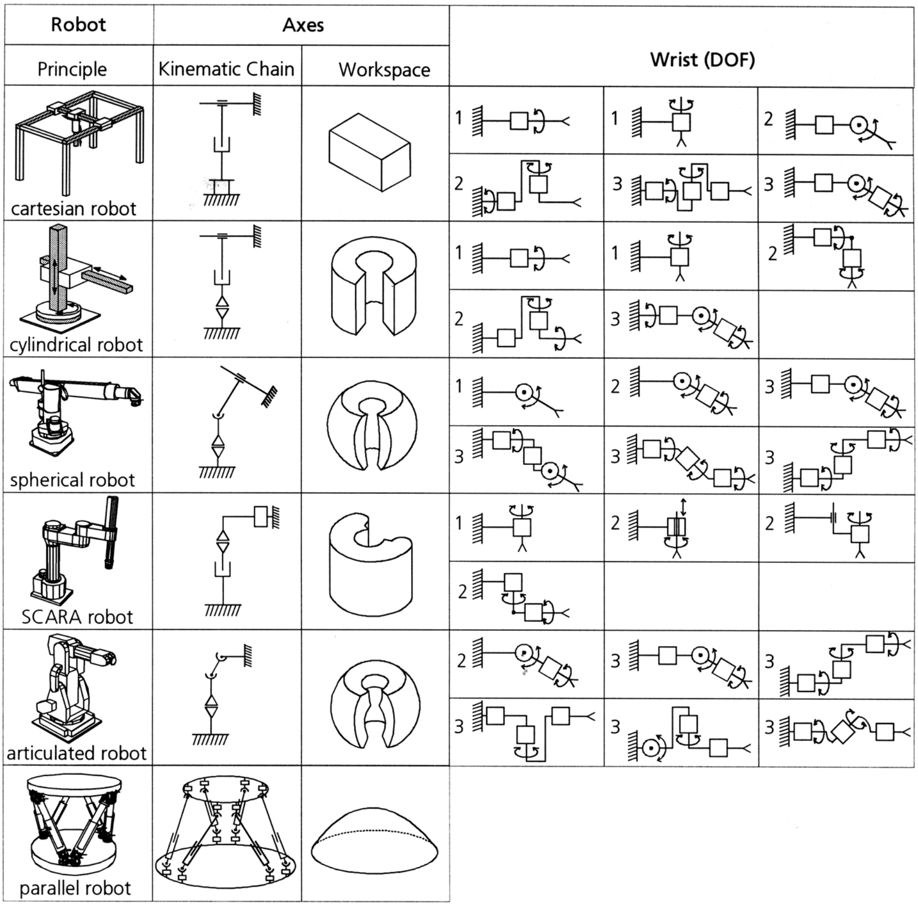


FIGURE 28.7 Typical arm and wrist configurations of industrial robots.

system. Today these robot types play only a minor role and are used for palletizing, loading, and unloading of machines. See Figure 28.10.

28.2.2.3 SCARA Type Robots

As a subclass of cylindrical robot, the SCARA (Selective Compliant Articulated Robot for Assembly) consists of two parallel rotary joints to provide selective compliance in a plane which is produced by its mechanical configuration. The SCARA was introduced in Japan in 1979 and has been adopted by numerous manufacturers. The SCARA is stiff in its vertical direction but, due to its parallel arranged axes, shows compliance in its horizontal working plane, thus facilitating insertion processes typical in assembly tasks. Furthermore, its lateral compliance can be adjusted by setting appropriate force feedback gains. SCARA's direct drive technology fulfills in all potentials: high positioning accuracy for precise assembly, fast and vibration-free motion for short cycle times, and advanced control for path precision and controlled compliance. Figure 28.11 shows the principle of a direct-drive SCARA.

28.2.2.4 Articulated Robots

The articulated robot arm, as the most common kinematic configuration, consists of at least three rotary joints by definition. High torque produced by the axes' own weight and relatively long reach can be counterbalanced by weights or springs. Figure 28.12 displays a typical robot design.

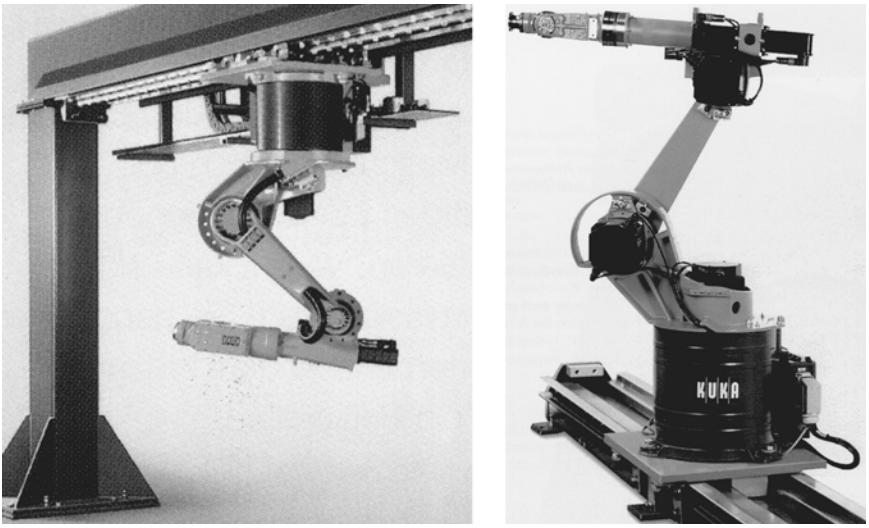


FIGURE 28.8 Floor and overhead installations of a six-DOF industrial robot on a translational axis, representing a kinematically redundant seven-DOF robot system. (Courtesy of KUKA.)

28.2.2.5 Modular Robots

For many applications, the range of tasks that can be performed by commercially available robots may be limited by their mechanical structures. Therefore, it may be advantageous to deploy a modular robotic system that can be reassembled for other applications. A vigorous modular concept that allows universal kinematic configurations has been proposed:

- Each module with common geometric interfaces houses power and control electronics, an AC servo-drive, and a harmonic drive reduction gear.
- Only one cable, which integrates the DC power supply and field bus signal fibers, connects the modules.
- The control software is configured for the specific kinematic configuration using a development tool.
- A simple power supply and a PC with appropriate field bus interfaces replace a switching cabinet.

Figure 28.13 illustrates the philosophy of this system and gives an example.

28.2.2.6 Parallel Robots

Parallel robots are distinguished by concurrent prismatic or rotary joints. Two kinematic designs have become popular:

- The tripod with three translatory axes connecting end effector, plate, and base plate, and a two-DOF wrist.
- The hexapod with six translatory axes for full spatial motion.

At the extremities of the link, we find a universal joint and a ball-and-pocket joint. Due to the interconnected links, the kinematic structure generally shows many advantages such as high stiffness, accuracy, load capacity, and damping.[11,21] However, kinematic dexterity is usually limited.

Parallel robots now work in many new applications where conventional serial chain robots reached shown their limits — machining, deburring, and part joining, where high process forces at high motion accuracy are overwhelming. Parallel robots can be simple in design and often rely on readily available, electrically or hydraulically powered, precision translatory axes.[12] Figure 28.14

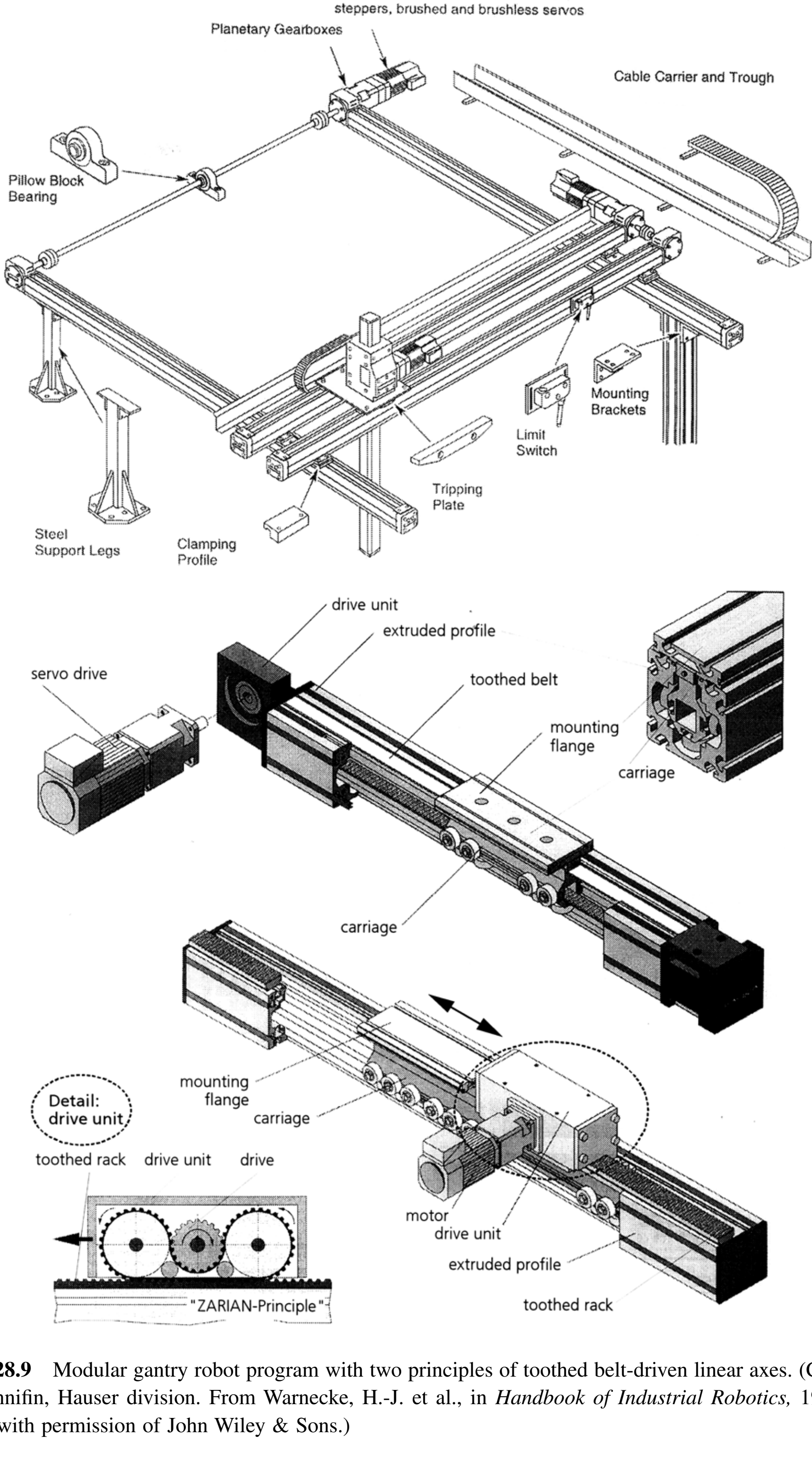


FIGURE 28.9 Modular gantry robot program with two principles of toothed belt-driven linear axes. (Courtesy of Parker Hannifin, Hauser division. From Warnecke, H.-J. et al., in *Handbook of Industrial Robotics,* 1999, p. 42. Reprinted with permission of John Wiley & Sons.)

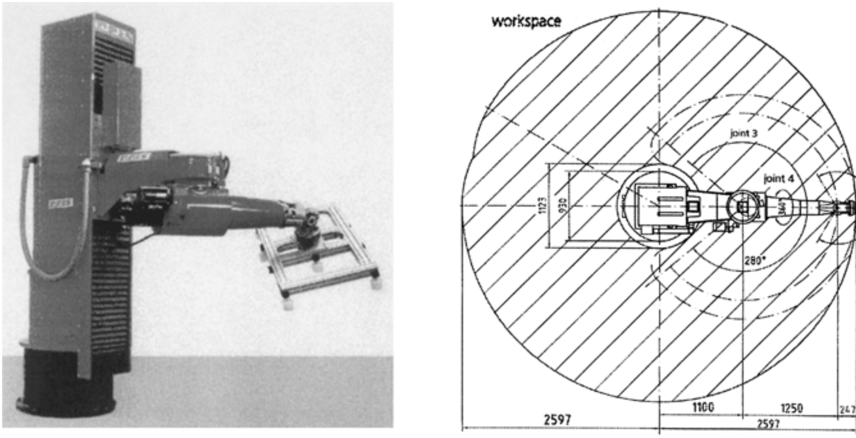


FIGURE 28.10 Five-DOF cylindrical robot with depiction of its workspace (top view, in millimeters). (Courtesy of Reis Robotics.)

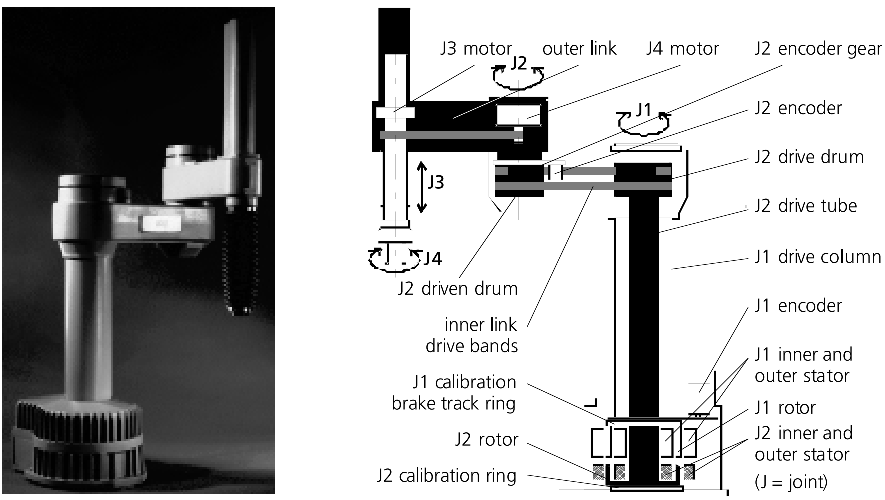


FIGURE 28.11 View of a SCARA robot (left) and cross-section through its direct drive arm transmission. (Courtesy of Adept.)

gives examples of tripod and hexapod platforms. Although parallel manipulators have been introduced recently and their designs are quite different from those of most classical manipulators, their advantage for many robotics tasks is obvious, and they will probably become indispensable.

28.2.3 Industrial Robot Application

28.2.3.1 Benefits of Robot Automation

The development of robot automation is characterized by a dramatic improvement in functional capabilities as well as rapidly falling price/performance ratios (technology push). There is also an increase in the demand for automation solutions, generated by the constant striving of industrial companies, in particular those subjected to international competition, to reduce costs and to improve

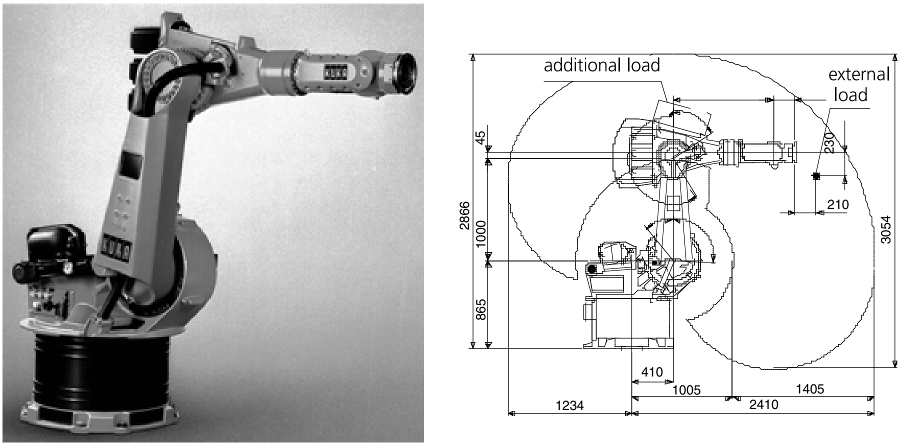


FIGURE 28.12 Articulated robot and its workspace. Note the gas spring that acts as a counterbalance to the weight produced by axis 2. (Courtesy of KUKA.)

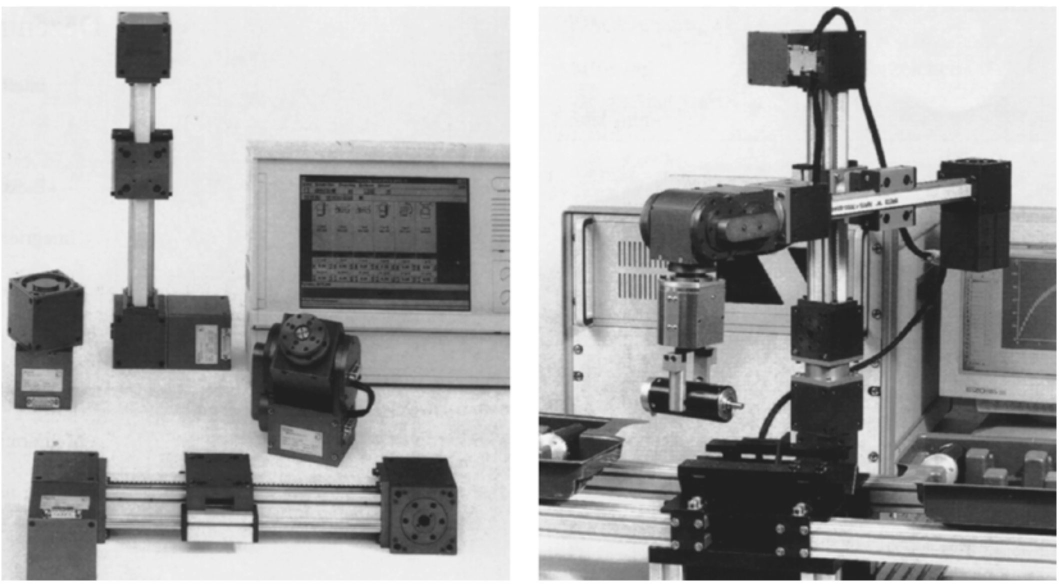


FIGURE 28.13 Modular robot system consisting of rotary and translatory axis modules, grippers, and configurable control software. (Courtesy of Amtec.)

product quality (market pull). Falling unit costs and improved robot system performance led to new automation solutions, many of them outside classical industrial robot applications, such as:

- Food industry (material flow automation with functions such as packaging, palletizing, order picking, sorting, warehousing, processing, etc.)
- Mail order and postal services (material flow automation)
- Airports, train stations, freight terminals, etc. (material flow automation)
- Consumer goods (processing, material flow automation)
- Chemical, pharmaceutical, and biotechnical industries (processing, material flow automation)

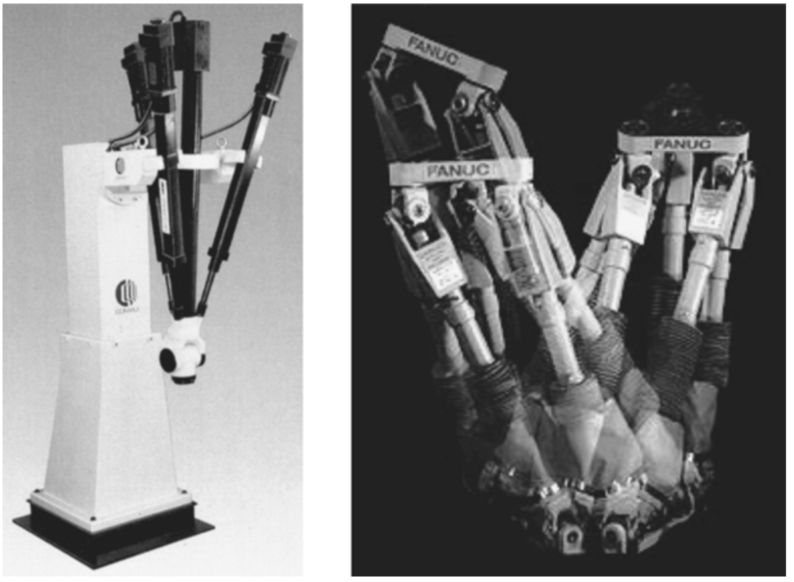


FIGURE 28.14 The COMAU Tricept, a six-DOF tripod and the FANUC FlexTool Steward platform with six servo-spindle modules connecting the bottom and moving plate. (Courtesy of COMAU and FANUC Robotics.)

Robot manufacturers and integrators now supply low-cost flexible workcells with standard configurations, which can be rapidly integrated into existing production systems for standard applications. Even small volume operations can be effectively automated for functions such as parts welding and cutting, flexible assembly, packaging, and palletizing.

A recent survey among German manufacturers reviewed the benefits realized from investing in robot automation (see Figure 28.15). Besides cost effectiveness, there are many other reasons a company considers in selecting a robot system, e.g., effect on parts quality, manufacturing productivity (faster cycle time), yield (less scrap), reduction in labor, improved worker safety, and reduction of work in progress.

28.2.3.2 Robot Workcell Planning and Design

Once the desired benefits and requirements are identified, specification, commissioning, and the process of putting the robot system into operation must be approached in a systematic manner. Installing a robot workcell is best done in a multistep process that involves consideration of robot, the products to be handled by the cell, other production equipment in the cell, layout, scheduling, material flow, safety, maintenance, and training. See Figure 28.16.

Numerous planning tools support the planning and design of the robot workcell. These so-called computer-aided production engineering (CAPE) tools assist in effectively designing, evaluating, and controlling production facilities. They help meet performance requirements and cost and time constraints. Suppliers can be selected on the basis of price and on their ability to offer integrated services during workcell planning, implementation, and operation. In fact, clients and robot system integrators often establish close partnerships that last over the life of the system. The case studies reviewed below clearly show the importance of such partnerships for the success of installation and operation of robot cells.

28.2.3.3 Case Study: Automated High-Frequency Sealing in Measuring Instruments

28.2.3.3.1 Introduction

The company Rohde & Schwarz is an established leader in the field of electronic systems and measuring instruments. It attained this position by successfully offering high quality standard products and custom-designed systems. Its production is characterized by small lots, short delivery

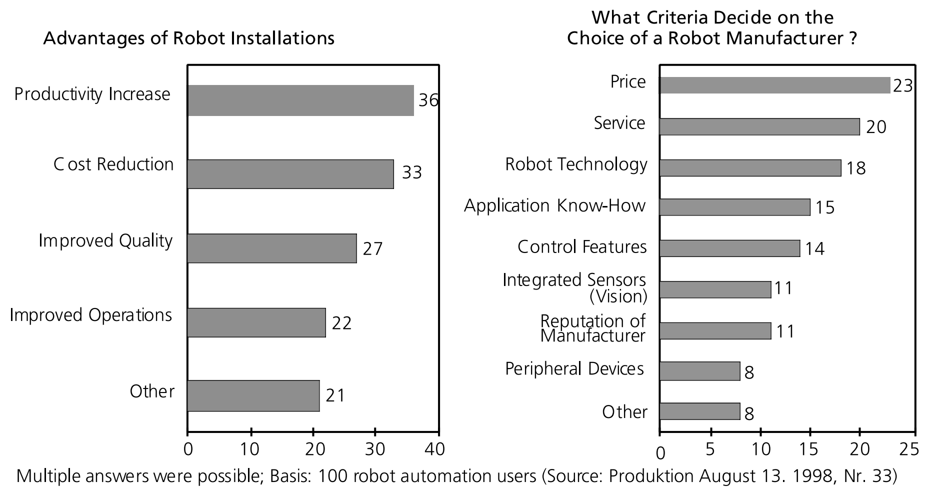


FIGURE 28.15 Survey of benefits from robot automation and criteria for selecting suppliers.

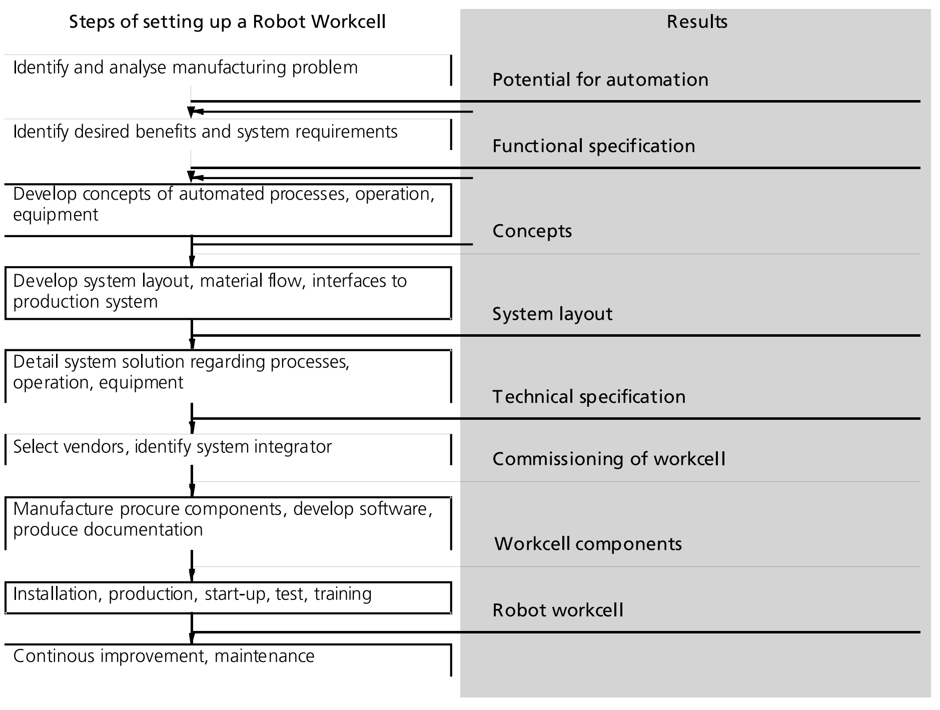


FIGURE 28.16 Typical steps for launching a robot workcell.

times, and short development lead times. By investing in an automated assembly system for measuring instrument cases, the company estimated that it could manufacture the products at lower costs. The cases are composed of several frame parts. Each frame part is separated by a metal cord for screening against high frequency (hf) radiation (see Figure 28.17).

The cases have various dimensions (six heights, three widths, and three depths). The company produces about 1000 product variants with customer-specific fastening positions for the insertion of the measuring instruments. The assembly line is split to allow order-independent preassembly and order-specific final-assembly (see Figure 28.18).

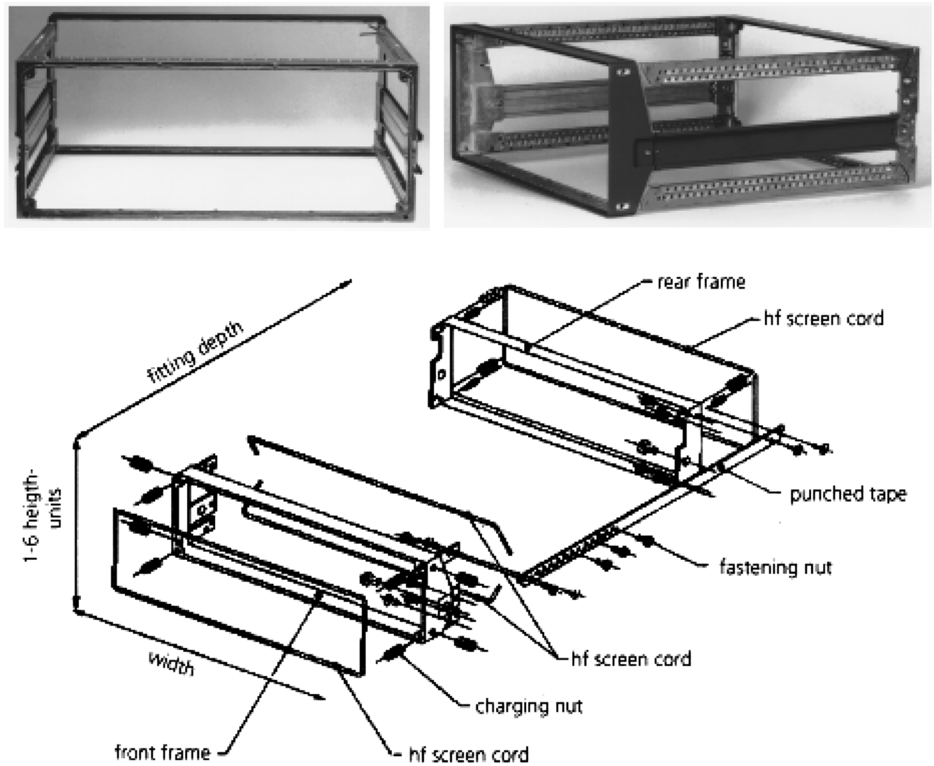


FIGURE 28.17 Typical frame design (top left and right) and frame-components (bottom) of cases for measuring instruments.

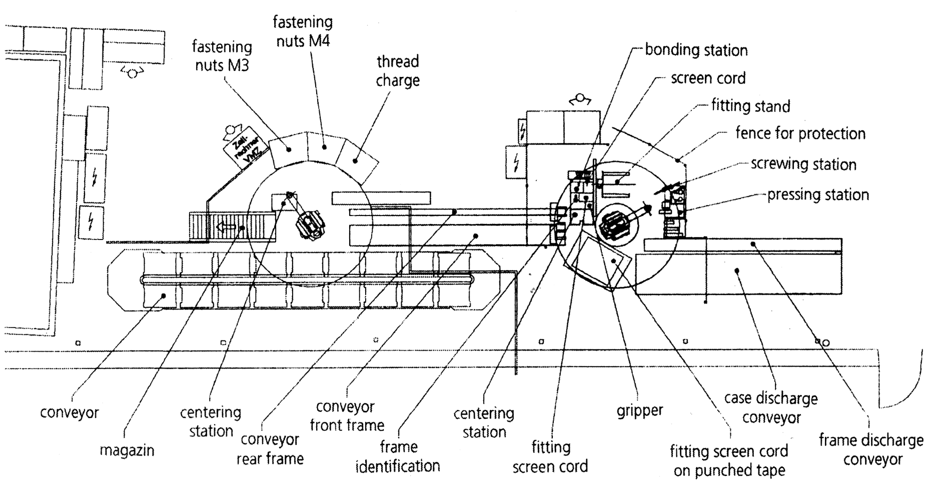


FIGURE 28.18 Layout of the preassembly (left) and final assembly cell (right).

28.2.3.3.2 Pre-Assembly of Cases

Automatic stations in the preassembly cell press in fastening nuts and screw in several threaded bolts. An industrial robot handles the frame parts. After removing the frames from the supply pallets, the robot brings the frame into a mechanical centering device for fine positioning and for eliminating tolerances in the pallets. It is possible to achieve exact positioning of the frame in the robot gripper.

During the pressing operation, the robot positions and fixes the frame in the press station. The pressing operation requires a press force of about 3000 N. A compliance system is integrated into the gripper to eliminate tolerances in the frame dimensions. The robot also positions and fixes the frames in the screwing station. A system controls the rotation angle, screwing torque, and screwing depth to consistently reproduce a screwing depth of 0.1 mm.

After terminating the preassembly, the robot places the frames on a conveyer system. The conveyer links the preassembly and final assembly cells. The conveyer belts are separated into belt pairs for front and rear frames.

28.2.3.3.3 Final-Assembly of the Cases

The final assembly consists of:

- Fitting the metal cord for high frequency screening into the frames
- Order-specific pressing of fastening elements
- Screwing together all frames that form the finished case
- Lettering the finished case

One of the most interesting technical potentials for automation was the assembly of the metal cord for high frequency screening into each frame. The metal cords are nonrigid parts. At the beginning of the project, the company had little experience in automated assembly of cords. The cords have no rigidity; they can only transmit tensile forces. The results of other forces and torques and undefined deformations were unforeseen. The influence of temperature variations had to be considered. An additional problem is reproducibility of cord diameter. Two metal cords with different diameters (2.0 mm and 3.0 mm) have to be fit into four different running slots. The 250-m cords are supplied on coils. In the slot of the rear frame, it is necessary to insert adhesive points to give the cord the required stability.

Several basic principles for fitting the metal cord into the slots were investigated. Fitting with an oscillating plunger was the best method for assembling the cord into the slots.

Four geometrically different plungers were necessary for the different running slots to achieve a minimum of plunger changing time, all plungers were integrated in the robot tool. See Figure 28.19. Depending on the slot type, the right plunger is positioned and coupled with the oscillating motor. A cord cutting system is integrated into the robot tool to obtain the right length of the cord (depending on the dimensions of the frames). It also includes an adhesive-dispensing system to set the adhesive spots into the slots.

After fitting the metal cord into the front inside, front outside, rear and side ledge frames the fasteners for the inserts are pressed in order-specific positions into the side ledges. For this operation the robot takes a ledge with the required length from a magazine and brings it to a press station. A guide rail defines the exact position. The fasteners are blown automatically from the feeder through a feed pipe to the press position. Force and position of the press plunger are monitored during the press operation. Figure 28.20 shows how the sealing tool fits the cord into the rear frame of the case and the subsequent screwing of all frame components, which is also done by the robot.

The robot first moves to the screwing position. The screws are blown automatically through the feed pipe on the feeder to the screwing tool. To achieve a perfect result, rotation angle and screwing torque are monitored.

Depending on the construction of the case, it is important to have accessibility from four directions throughout the assembly process, and it was necessary to install a clamping device that can turn the case in all required positions. The result was a system consisting of standard components that can clamp more than 25 cases with different dimensions. Figure 28.21 shows the preassembly cell (left robot in the layout in Figure 28.18) and the final assembly cell with the flexible clamping system (right robot in Figure 28.18). For quick tool changes, the robot arm has an automatic tool changing system. Each tool can be picked up within a few seconds.

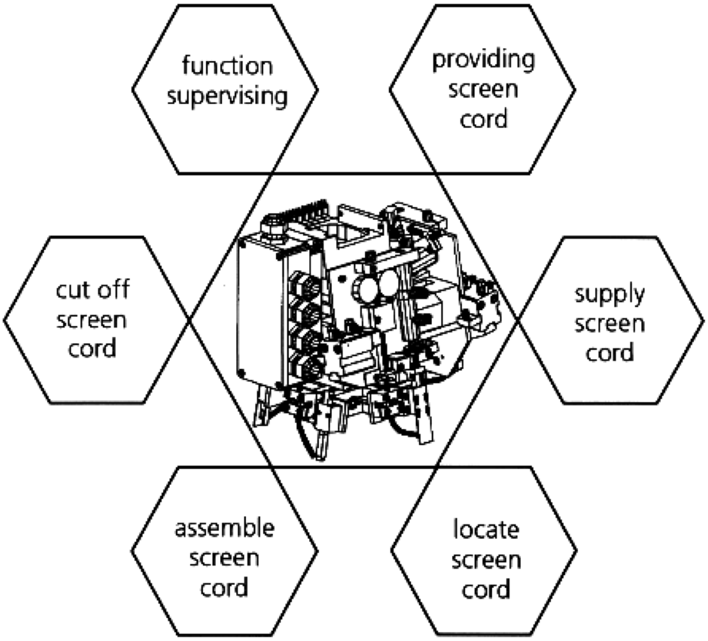


FIGURE 28.19 Tool system tasks in automated high-frequency sealing.

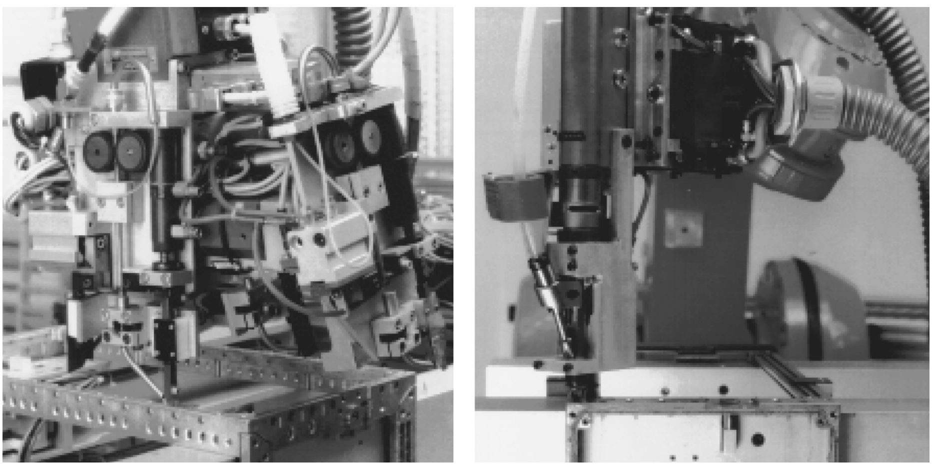


FIGURE 28.20 Robot tool for fitting of metal cord in front frame (left) and for screwing of frame parts.

28.2.3.3.4 Conclusion

Tasks with extensive numbers of assembly steps and production volumes of less than 10,000 units per year can be automated in a cost-effective way. Such automation projects are of special interest for small and medium sized companies in the electronic industry. Almost all components developed for this system can be used in other assembly systems with only small modifications. The main objective of the robot investment was to combine high product quality with improved cost effectiveness. A pay-back period of 3 to a maximum 4 years on the basis of 10,000 produced units per year, was set as the break-even for an investment of some 700,000 DM in equipment cost and 200,000 DM in engineering costs. Since the workcell was installed in 1993, production volume has, increased to more than 16,000 units per year so that a pay-back period of well below 3 years

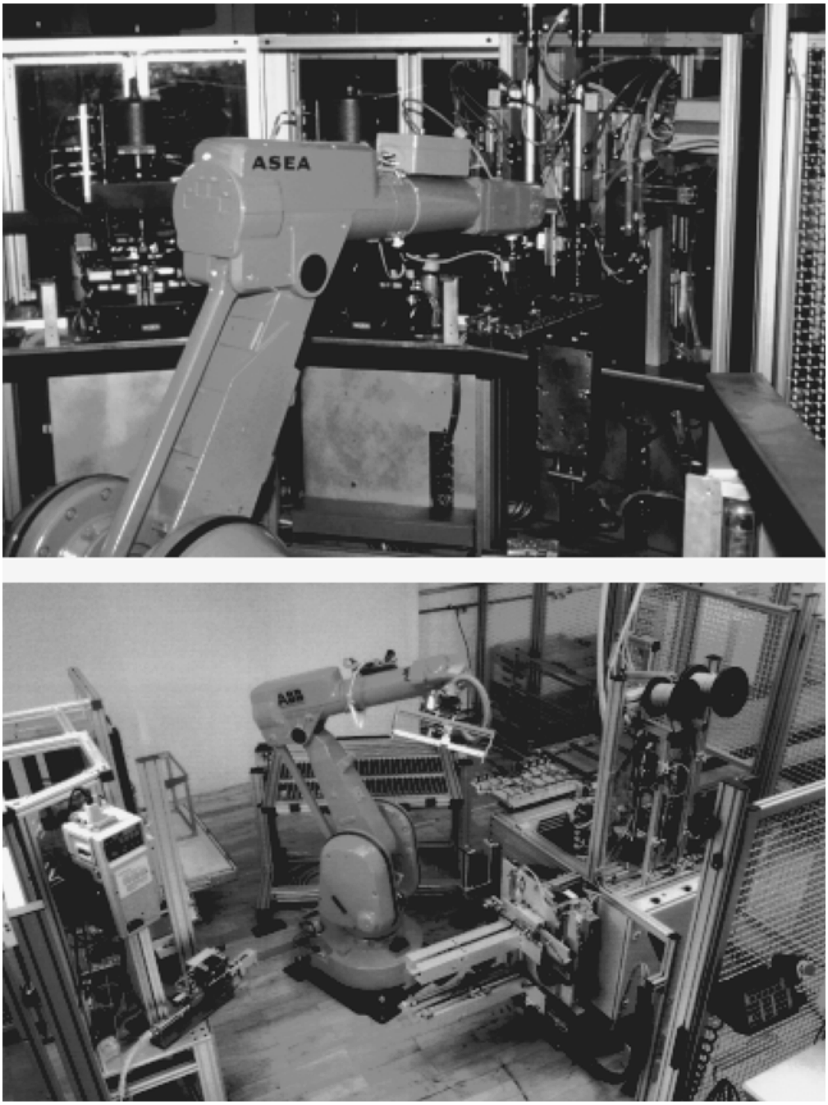


FIGURE 28.21 Preassembly cell (top) and final assembly cell (bottom) with flexible clamping system.

was achieved. The decision to invest in a robot system for the complicated process of sealing and assembling variable frames turned out to be more profitable than originally estimated.

28.3 Service Robots

28.3.1 From Industrial Robots to Service Robots

Early industrial robots were found in many nonmanufacturing applications:

- Inspection tasks in hazardous environments
- Laboratory automation
- Automated pharmacy warehousing
- Storage and retrieval of data cartridges in computing centers

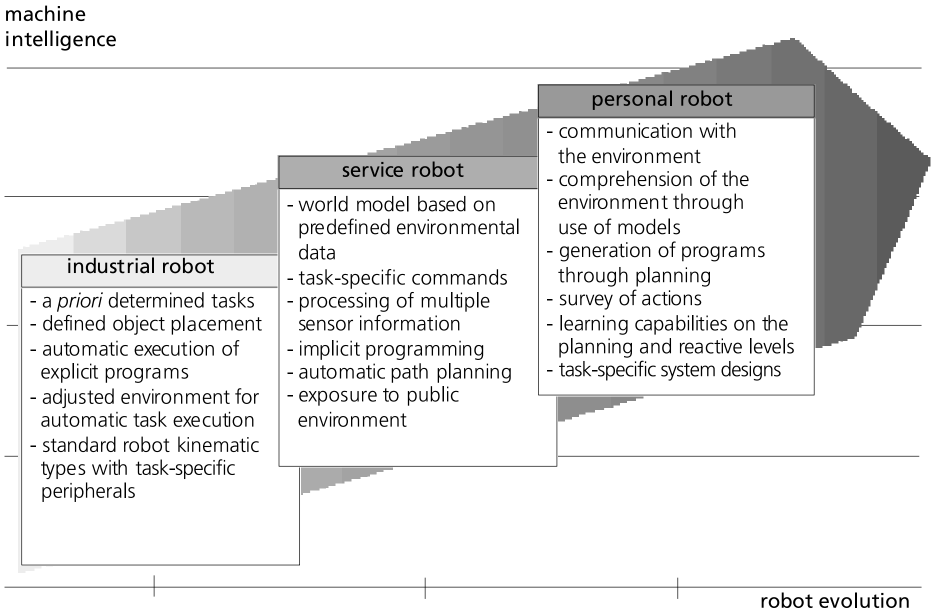


FIGURE 28.22 From industrial robots to service robots — the evolution of machine intelligence.

Robot application in nonmanufacturing fields has been on the rise as key technologies have become more available. Sensors in combination with advanced perception algorithms allow robots to function in partly or even completely unstructured environments. Fast interactions between sensing and action account for effective and robust task execution, even in dynamically changing situations.

A definition recently suggested by IFR (the International Federation of Robotics) offers a description of the main characteristics of service robots, their exposure to public, and task execution in unstructured environments.[15] Service robots are considered extensions of industrial robots.[19]

> Service robots are robots which operate semi or fully autonomously to perform services useful to the well being (hence, non-manufacturing) of humans and equipment. They are mobile or manipulative or combinations of both.

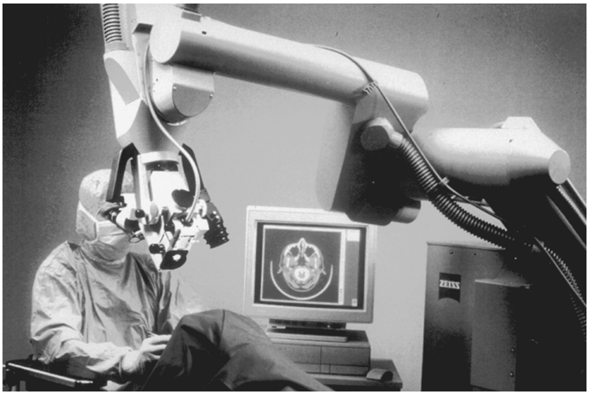
IFR has adopted a preliminary system for classifying service robots by application areas:

- Servicing humans (personal, safeguarding, entertainment, etc.)
- Servicing equipment (maintenance, repair, cleaning, etc.)
- Performing autonomous functions (surveillance, transport, data acquisition, etc.) including service robots that cannot be classified in the previous categories.

Some scientists and engineers even predict a future for "personal robots,"[5,7] and visions depict these robots as companions for household tasks, gardening, leisure, and even entertainment. The evolution of robots can be characterized by the level of machine intelligence implemented for task execution. See Figure 28.22.[17]

28.3.2 Examples of Service Robot Systems

Service robots are designed for the execution of specific tasks in specific environments. Unlike an industrial robot, a service robot system must be completely designed. New concepts stress the possibility of using preconfigured modules for mechanical components (joints) and information processing (sensors, controls). The following is a survey of different service robot systems, based on the IFR classification scheme.



MKM

Servicing humans — The medical manipulator (MKM) produced by Carl Zeiss, Germany, consists of a weight-balanced servo-controlled six-DOF arm, a computer control, and a graphical workstation for visualization and programming. It carries a surgical microscope. Movements follow preprogrammed paths or are generated manually by a six-DOF input device (space-mouse) or voice.

MANUS

The MANUS arm of Exact Dynamics, The Netherlands, is a wheel-chair mountable six-DOF lightweight manipulator meant for persons with severe disabilities. The combination of wheelchair and manipulator helps in executing simple tasks such as opening doors, preparing coffee, etc. The arm folds discreetly while not in use. The man–machine interface for motion command can be individually adjusted to the person's abilities and can be a mouth whistle, voice, joystick, or any other adequate device.

CASPAR

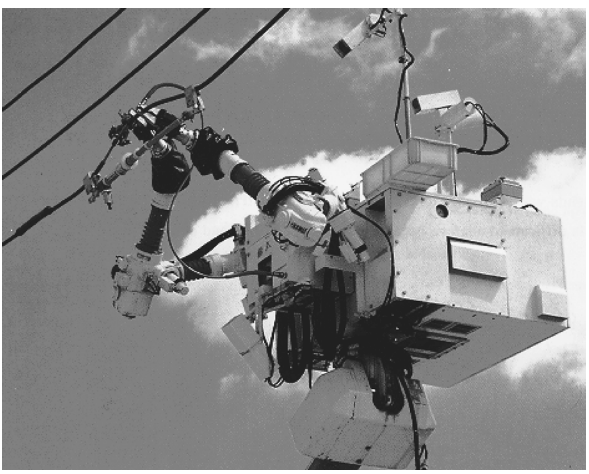
CASPAR (Computer Assisted Surgical Planning and Robotics) of ortoMAQUET, Germany, consists of an industrial robot mounted on a mobile base, a milling tool, and a calibration unit. The system assists the surgeon in orthopedic interventions such as hip surgery. On the basis of patient data, the placement of a hip prosthesis is simulated. All contours for a perfect fit are milled with remarkable precision under surgical supervision.

Electrolux

Electrolux, Sweden, introduced the first lawn mower powered by solar cells. Some 43 solar cells transform sunlight into electrical energy. The solar mower is fully automatic and eliminates emissions into air and makes almost no noise.

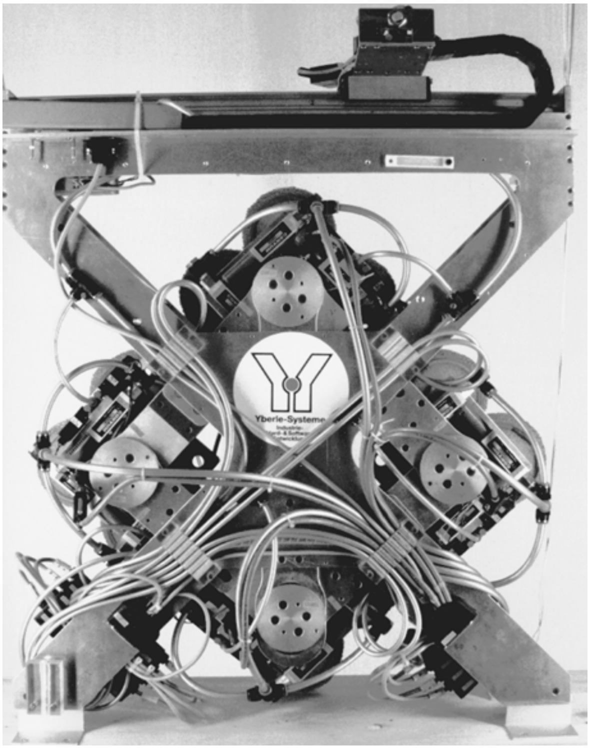
Skywash

Servicing equipment — With two Skywash systems (Putzmeister Werke, Germany) in parallel operation, a reduction of ground times per washing event for factor 3 (wide body) aircraft and factor 2 (narrow body) can be achieved. Skywash integrates all features of an advanced robot system: pregeneration of motion programs by CAD aircraft models, object location by 3D-sensors, tactile sensor-controlled motion, redundant arm kinematics (11 DOFs) installed on a mobile base, and full safety features for maximum reliability. From a rough placement relative to the aircraft, Skywash operates under human supervision.



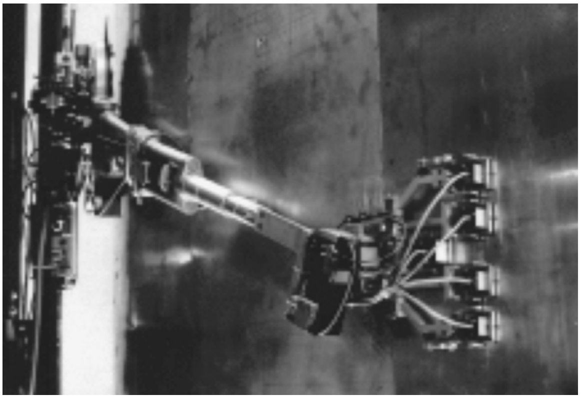
Master–slave two-armed robot

A master–slave two-armed robot (Yaskawa, Japan) carries out operations with live wires (cutting, repair, etc.) of up to 6600 V capacity. A truck-mounted boom carries the manipulator arms which are operated from a cabin.



Rosy

Rosy produced by Robot System of Yberle, Germany, climbs surfaces on suction cups to perform cleaning, inspection, painting, and assembly tasks. Tools can be mounted on the upper transversal axis. Navigation facilities allow accurate and controlled movements.



Robot for nuclear reactor outer core inspection

A robot for nuclear reactor outer core inspection (Siemens KWU, Germany) follows a modular approach. Each joint module with common geometric interfaces houses power and control electronics, an AC servo drive and a reduction gear. The robot travels along existing rails and maps the core surface by its end effector-mounted ultrasound sensors. Material flaws can be detected and monitored during reactor operations.

Cleaning robot

Performing autonomous functions — Cleaning robots have entered the market. Larger surfaces (central stations, airports, malls, etc.) can be cleaned automatically by robots with full autonomous navigation capability. The HACOmatic of Hako-Werke, Germany, is an example.

CyberGuard of Cybermotion Inc., United States, is a powerful tool that provides security, fire detection, environmental monitoring, and building management technology. The autonomous mobile robotic system features a rugged self-guided vehicle, autocharger docking station, array of survey instrumentation, and dispatcher software that provides system control over a secure digital spread-spectrum link.

The HelpMate of Pyxis, United States, is a mobile robot for courier services in hospitals, introduced in 1993. It transports meals, pharmaceuticals, and documents along normal corridors. Clear and simple user interfaces, robust robot navigation, and ability to open doors and operate elevators by remote control make it a pioneering system in terms of technology and user benefit. More than 100 installations are currently operating in hospitals with excellent acceptance by personnel.

The Care-O-Bot (Fraunhofer IPA, Germany) helps achieve greater independence for elderly or mobility-impaired persons and helps them remain at home. It offers multimedia communication, operation of home electronics, active guiding or support, and will fetch and carry objects such as meals or books.

28.3.3 Case Study: A Robot System for Automatic Refueling

Design and setup of service robot workcells require a vigorous systems approach when a robot is designed for a given task. Unlike industrial robot applications, a system environment or a task sequence generally allows little modification so that the robot system must be designed in depth. A good example of a service robot system design for automation of a simple task is the following.

28.3.3.1 Introduction

The use of a refueling robot should be convenient and simple, like entering a car park. Upon pulling up to the refueling station the customer inserts a credit card and enters a PIN code and refueling order. A touch on the start button of a touch screen activates the refueling. The robot opens the tank flap and docks on the tank cap. The robot then places the required grade and amount of fuel

CyberGuard

HelpMate

Care-O-Bot

in the open tank — automatically, emissions-free, and without losing a drop. The task was to develop a refueling robot geared to maximum customer convenience and benefit.

A consortium consisting of the ARAL mineral oil company and Mercedes-Benz and BMW set out to turn this vision into reality. Besides increasing comfort and safety, the system has significance in the future because of:

- Higher throughputs by shorter refueling cycles
- Reduced surface requirements of refueling stations
- No emissions or spillage
- Controlled and safe refueling

Customer benefits include

- Fully automatic vehicle refueling within 2 min
- Possibility of robotic refueling over 80% of all vehicles that have their filler caps on the rear right-hand sides
- Minimum conversion work on automobiles
- Up to five fuel grades available without producing emissions or odors
- Layout of refueling station that satisfies the appropriate ergonomic requirements
- Controlled, reliable system behavior in the event of unexpected human or vehicle movement or other disruptive factors
- Safe operating systems in areas at risk of explosion
- Economically viable equipment

Robot refueling is a typical use of an articulated service robot with characteristic properties:

- It can carry out its task safely without explicit knowledge of all possible situations and environmental conditions
- It can function when information on the geometric properties of the environment is imprecise or only partly known
- It creates confidence that encourages its use

28.3.3.2 Systems Design

Planning and design of service robot systems involves systematic design of mechatronic products (Schraft and Hägele,[18] Kim and Koshla,[94] and Schraft et al.[20]) followed by designing methods that will meet cost, quality, and life cycle objectives. The geometric layout and the overall configuration of the information processing architecture of the service robot are critical tasks. System design becomes more complex as requirements regarding dexterity, constraints, autonomy, and adaptivity increase. See Figure 28.23.

The technical specification of a service robot system can be divided into two successive phases: functional specification and system layout and architecture specification. This approach will be examined and applied to the development of the fuel refueling robot.

28.3.3.2.1 Functional Specification

Functionality is defined as the applicability of an object for the fulfillment of a particular purpose.[3] Various properties characterize an object and contribute to its definition of functionality. The works of Cutkosky[4] and Iberall[8] address the importance of understanding functionality when robots manipulate and interact with objects in a complex and dynamic environment. The functional specification phase develops:

- A list of the system's functional and economical requirements over its life cycle from manufacturing and operation to dismantling and recovery
- A formal description of the underlying processes in nominal and off-nominal modes

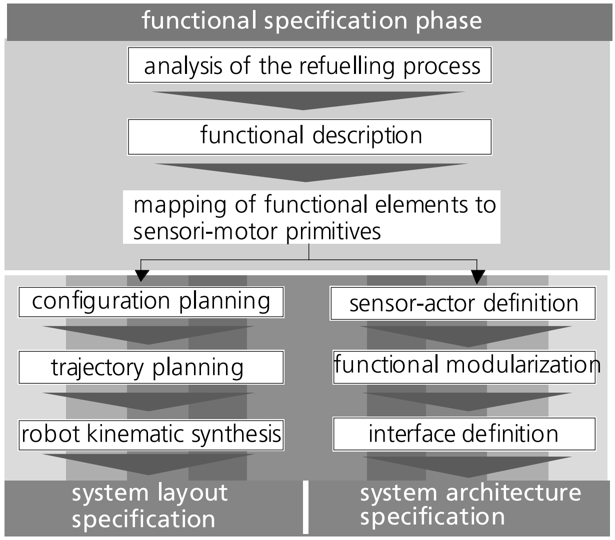


FIGURE 28.23 Technical specification of service robot systems. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

The analysis of service tasks is carried out similarly by process structuring and restructuring to define the necessary sequence and possible parallelism of all task elements. The focus lies in the analysis and observation of object motions and their immediate interactions as sensorimotor primitives.[2,13] Tasks are divided into:

- Elementary motions without sensor guidance and control (absolute motion control)
- Sensorimotor primitives defined as encapsulations of perception and motion that form domain general blocks for fast task strategies (reactive motion control)

The formalism for describing, controlling, and observing object motion in a dynamic environment concentrates on defining all relevant geometric, kinematic, and dynamic properties:

- Geometrical properties that identify quantifiable parameters (goal frames, dimensions, volumes, etc.)
- Kinematic properties that identify the mobilities of objects in trajectories
- Dynamic properties that describe how the object responds to forces or geometrical constraints

28.3.3.2.2 System Layout and Architecture Specification

The system layout specification comprises: the list of all devices required for task execution, trajectories and goal frames of analyzed objects, and robot kinematic parameters. After defining all devices, their geometry, spatial arrangement, and geometric constraints inside the workcell must be determined. The next step is trajectory planning of the automated task execution. It defines all geometric and kinetic entities such as goal frames, trajectories, permissible workspaces, and minimal distances to possible collision partners. Kinematic synthesis is the most complex step. It requires the optimal solution of a highly nonlinear and constrained problem. The task-based design requires the determination of:

- The number of degrees of freedom (DOFs)
- The kinematic structure
- The joint and link parameters
- Placement inside the robot workcell
- The location of the tool center point (TCP) relative to its last axes[16]

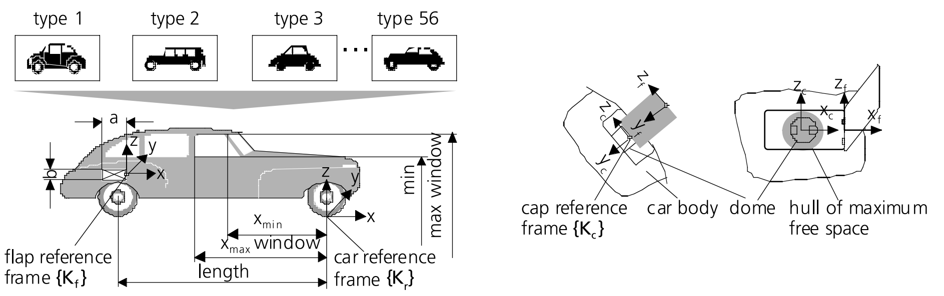


FIGURE 28.24 Registered car dimensions for automated refuelling. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

The quality of the manipulator design is expressed by objective functions such as dexterity, reachability, singularity avoidance, and kinematic simplicity.

The system architecture specification comprises the definitions of:

- All sensors and actuators with their logical interactions
- Logical interfaces between all data processing elements and their integration in a system architecture
- Man–machine interactions and their task level interfaces

Perceptive capabilities of the system result in the mapping of the task sequence into motion elements and sensorimotor primitives. The selection of the sensor depends on:

- The modality of information (force, distance, etc.)
- Dimensionality of the sensation
- Covering of the events defining possible transitions in the task execution
- Confidence in the observation that results from the observability of the event and the relevance of the sensor information.

28.3.3.3 Refueling Robot System Layout

The functional specification of the automated refueling describes the geometry, object motion, and its observability by perceptive elements in a straightforward manner:

Geometry — All robot movements must be limited to the car's rear section. The doors must not be obstructed or opened any time. The only reference for the coarse positioning of the car is the terminal. For 56 car types representing over 90% of Germany's car population, all relevant data regarding dimensions and flap and cap locations were registered (Figure 28.24).

Motion — The task sequence incorporates simple motion elements (e.g., move linearly, move circularly) and sensorimotor primitives like docking which requires a controlled approach toward dynamic goal frames (Figure 28.25).

Dynamic — Vertical vehicle movements may reach a frequency of over 1 Hz at a maximum velocity of 1 m/s. Sudden acceleration must result in safe emergency undocking.

The configuration of the system is shown in Figure 28.25. The concept of the refilling station suggests a simple layout and clear spatial perspective that should belie any complicated technology. The driver should simply have to drive up to the terminal, without having to stop the vehicle at a precise point. The robot is initially positioned out of sight. Only a refilling island 150-mm high is visible above the ground. All doors may swing open and people may exit the car any time. The terminal serves as a user-friendly customer interface and as a reference for the driver to conveniently position the car. The terminal can be reached, moved, and its height adjusted from the driver's window.

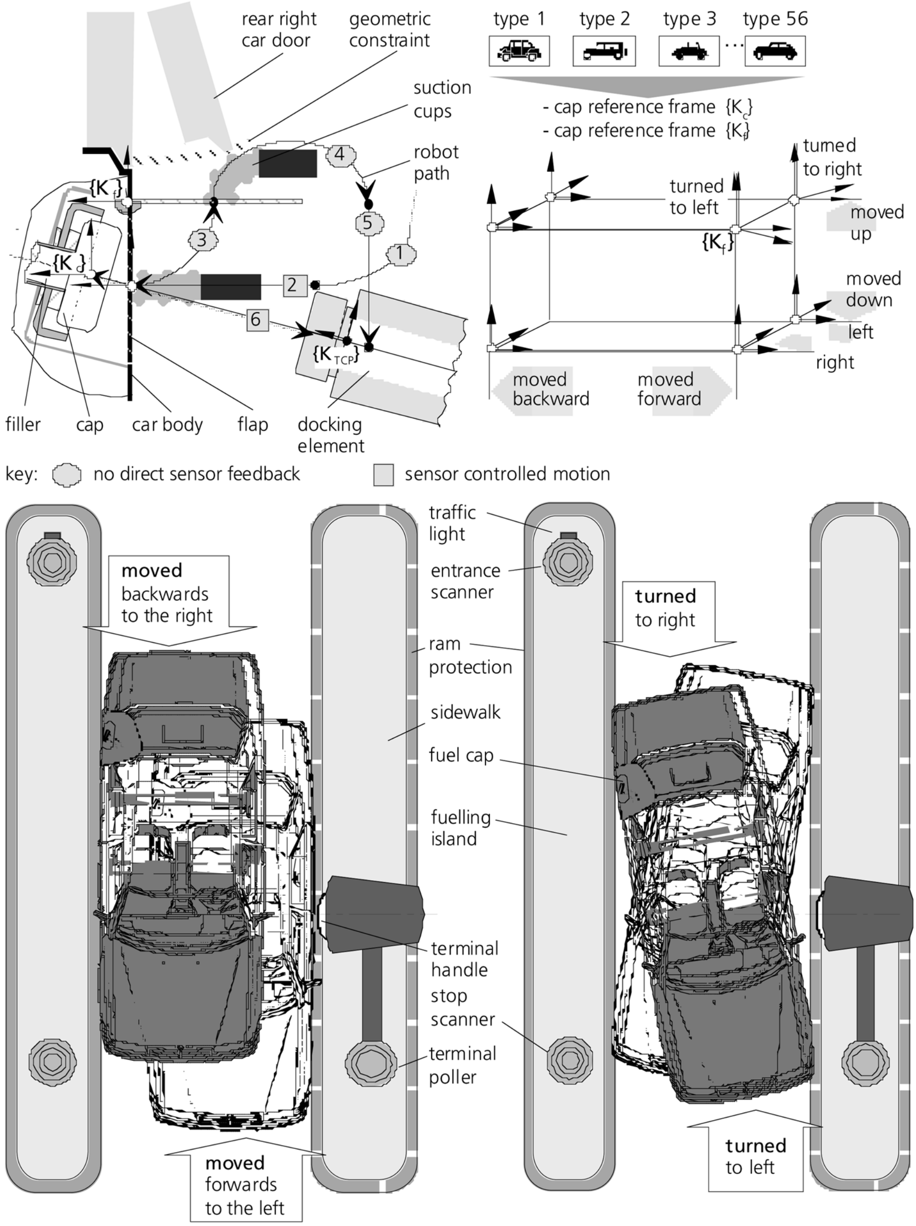


FIGURE 28.25 Layout of the automated fuel refilling system considering assumed extremal car locations in the filling station. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

Trajectory planning deals with the robot's movements covering one refilling cycle in nominal and off-nominal mode. Coming to a halt at the approach location the end effector (1) docks on to the flap, (2) turns the flap, (3) proceeds to the cap approach location, (4) docks on the cap, (5) turns the cap open, and (6) undocks and departs. All locations refer to the car's reference frame K_r. The range of car locations inside the refilling station is limited by the need to reach from the driver's window to the central axes of the terminal. Kinematic synthesis builds upon a trr:rrr structure. By numerical optimization, the best fitting arm kinematic must be found with respect to:

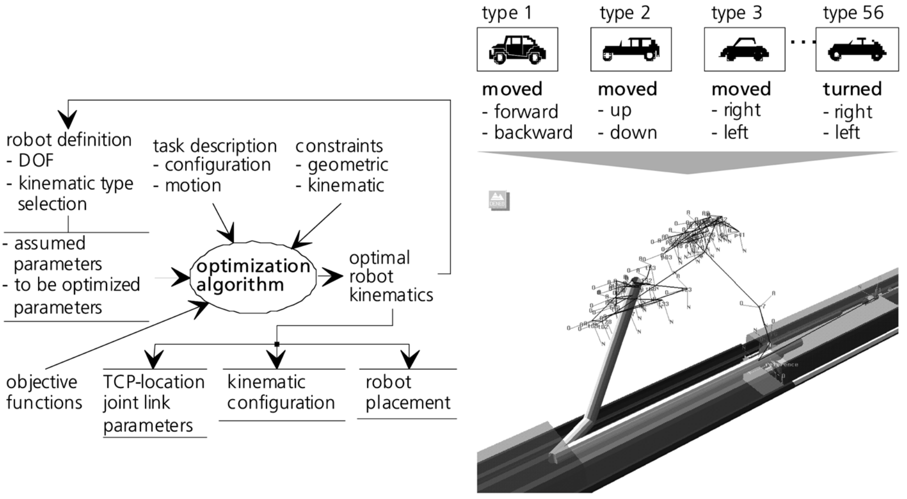


FIGURE 28.26 Robot kinematic optimization procedure (left) and goal frames and trajectories of a complete refilling cycle representing two extremal locations in the refilling station (right). (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

- Reachability suitable for any car type, considering assumed extremal positions or orientations
- Maximum clearance from potential collision objects
- Kinematic performance (dexterity)

The IGRIP CAPE tool was used as the kernel for the numerical simulation so that all motions, collision bodies, and geometric constraints could be interactively generated and visualized. See Figure 28.26.

28.3.3.4 Identification and Localization

Two general approaches for car identification were analyzed. See Figure 28.27.

Centralized data storage and retrieval — The car carries an individual serial number or type-specific code. After identification, the code is related to a specific motion program stored in a relational database. For any new car/type, the robot program and database reference will require immediate updates throughout all refilling stations. The transmitting of car-specific codes violates laws protecting personal data.

Decentralized data storage and retrieval — This preferred concept avoids these disadvantages. Vehicle identification takes place via a passive data carrier (transponder) located in the underfloor of the car. When the car is driven to the refilling station, the data stored in the transponder are scanned by a signal loop under the road surface. The data required include vehicle type, permitted fuel selection, maximum supply rate, and geometrical data, as Figure 28.28 depicts. These data are transferred into a standard robot motion program.

Since all trajectories and goal frames correspond to the car's reference frame, its location relative to the robot's base K_0 must be determined. Two laser scanners integrated into the entry and exit bollards scan a given surface of the filling station (Figure 28.29). Once the vehicle contour has been recognized and compared with the known dimensions of the detected car type, its exact position can be determined. The space defined by the vehicle contour and the curtain pattern of the scan define the safety zone. Any changes inside the zone such as human movements, opening doors, etc. are detected and temporarily freeze the robot.

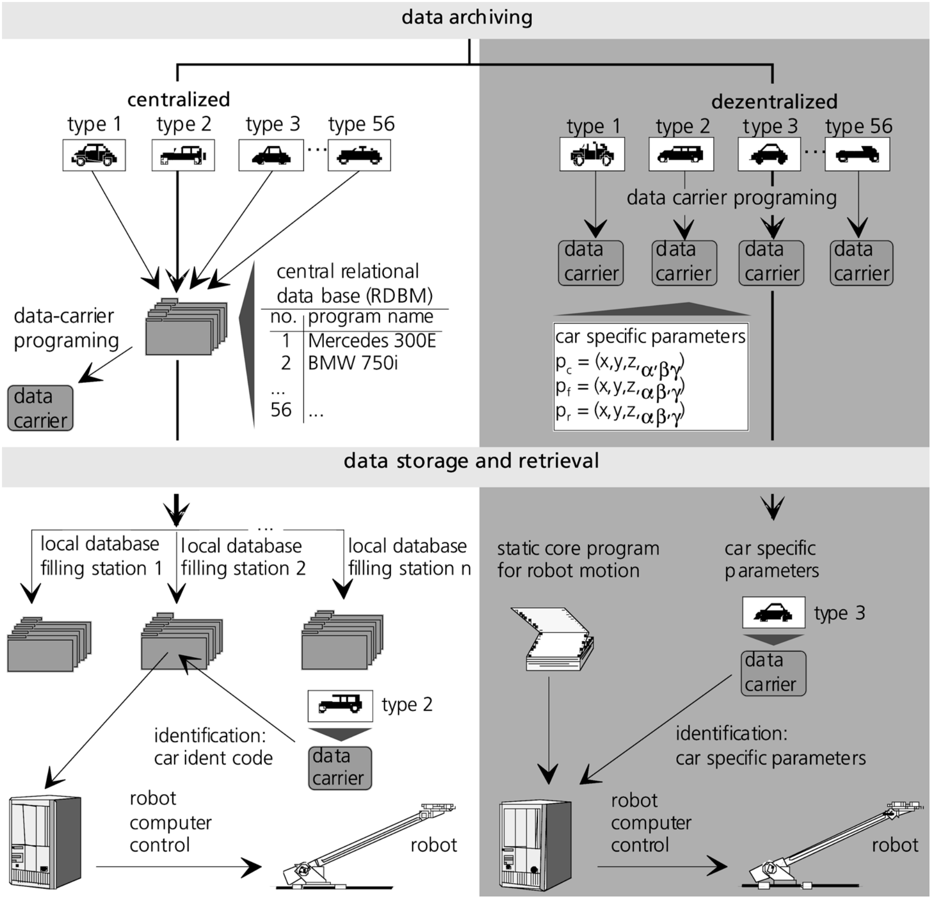


FIGURE 28.27 Centralized and decentralized data storage and retrieval for car-type identification and robot program selection. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

geometrical parameters	- location of flap and cap - opening trajectory of flap - flap type
fuel specific parameters	- allowable fuels - filling rate - tank volume
user data	- car type - standard fuel
auxiliary	- program version - program mode (standard/servicing) - service information - service programs for special car-types

FIGURE 28.28 Car-type specific data stored in the transponder. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

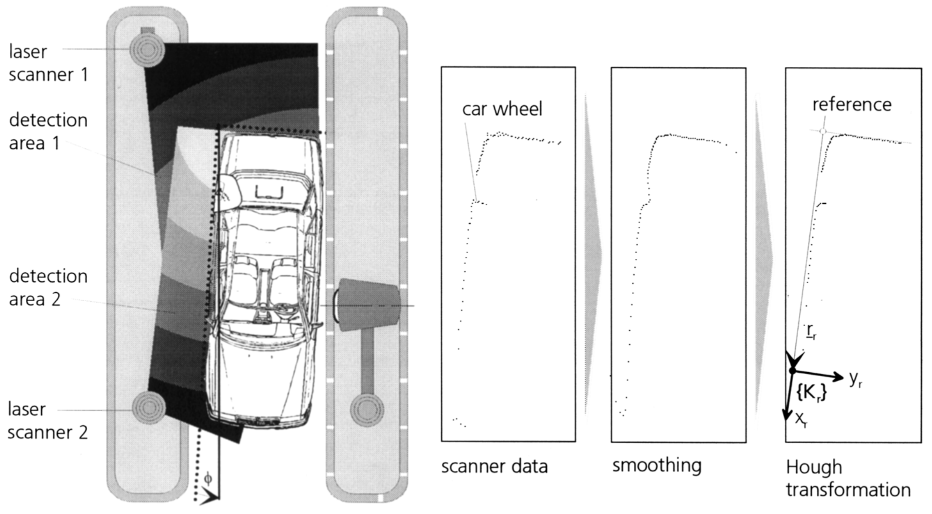


FIGURE 28.29 Vehicle location using two laser scanners with sensor data acquisition and modeling. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

28.3.3.5 Robot End-Effector

The end-effector as shown in Figure 28.30 is the interface between robot and filler flap or cap. The flap is lifted by two suction elements and opened by the robot's turning motion. A cylindrical docking-on element, the tank dome, establishes the mechanical connection and disconnection. When approaching the cap, the element is driven forward by a pneumatically powered tendon drive. The nozzle's entry and exit movements are driven by a second feed drive. The toothed ring recesses on the cap and turns it through 25° so that the fuel nozzle can be inserted. During refilling, the docking-on element's sealing action and integrated gas recirculation ensure that no emissions or odors are produced. The cap also permits refueling without difficulty.

In an emergency, for instance if the vehicle suddenly starts, the robot is disconnected instantly by the release of springs in the pneumatic cylinders. A graph representing the event structure and the step-wise increase in docking accuracy is depicted in Figure 28.31.

28.3.3.6 Docking Sensors

From their initial approach location (see Figure 28.25), the docking sensors detect and follow the reflectors on the filler flap and cap. LEDs pulse infrared or deep red light through fibers that illuminate the scene in front of the end effector. The line feed sensor receives the reflected light signal through a fiber-optic arrangement integrated in the docking-on element. To reach signal cycles of up to 200 Hz, the thresholds produced by the contrast between reflecting tape and its less reflecting vicinity are processed. The three fibers with their opening angles of some 60° cover three 120°-segmented lines about the optical axis as Figure 28.32 depicts.

The threshold of the reflected light produces signal peaks detected by corresponding pixel segments on a single line sensor. The positions of the peaks on each line sensor segment are measures of optical axis' displacement (ε_x, ε_y) from the reflectors center. This displacement is transmitted to the robot control which corrects end effector motion to the center of the reflector. The high sensor cycle time allows dynamic goals to be tracked effectively.

28.3.3.7 Experiments and Further Developments

The robot forms a compact functional unit with the refilling island and the delivery technology. The robot pulls out the correct fuel hose and nozzle based on the customer's choice of fuel.

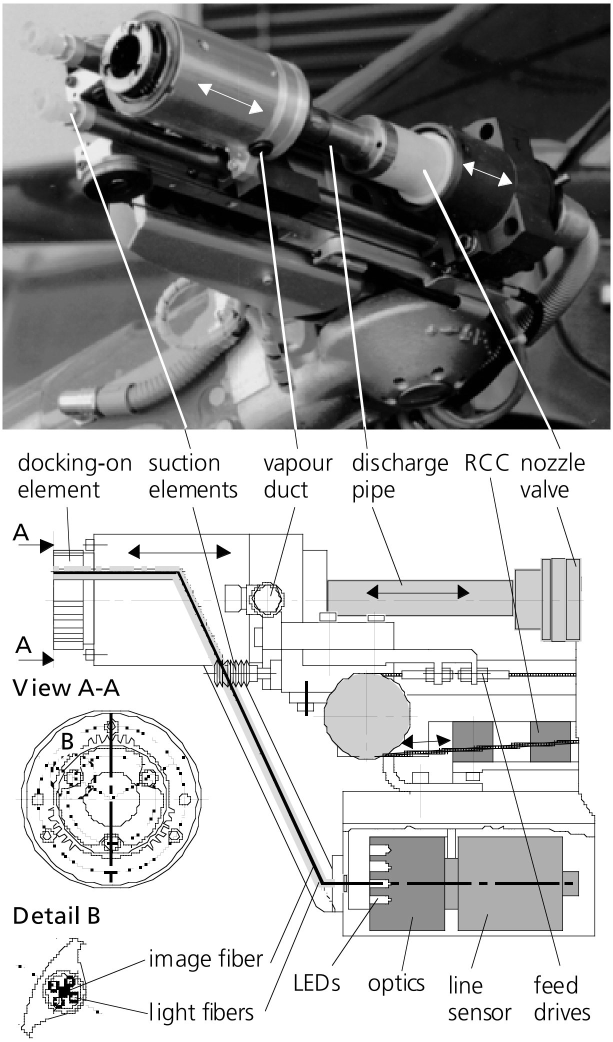


FIGURE 28.30 End-effector for automatic refueling. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

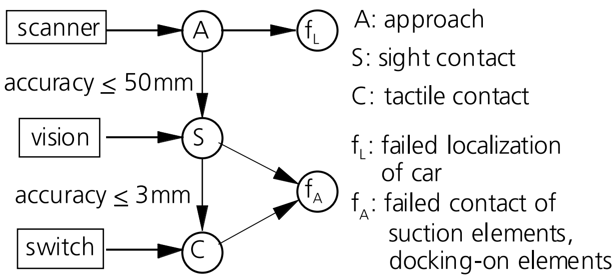


FIGURE 28.31 Event structure of the docking process. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

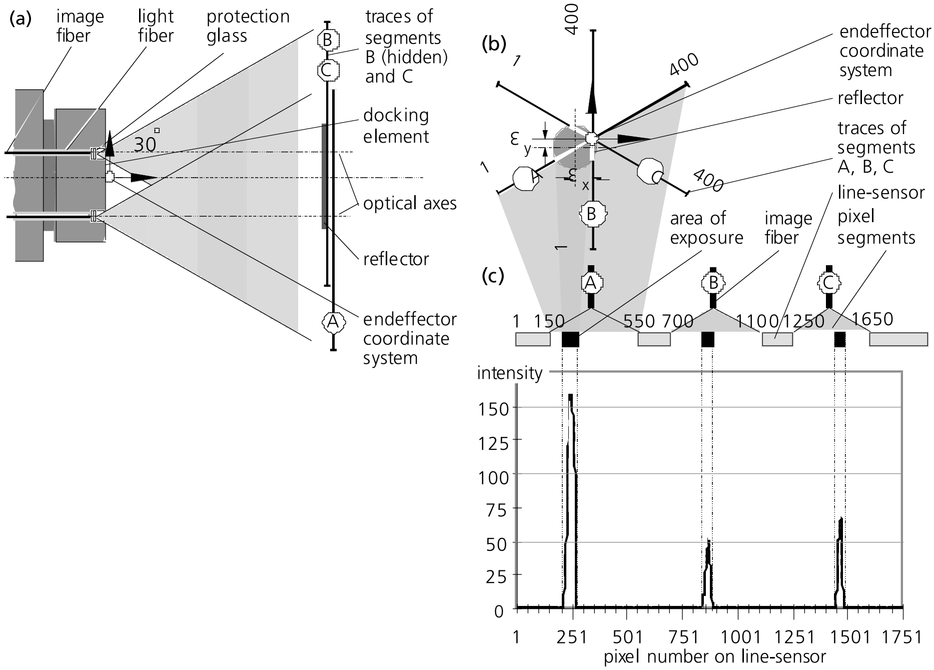


FIGURE 28.32 Working principle of the docking sensor. (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

FIGURE 28.33 View of a prototype installation at Fraunhofer IPA. A car being refueled by a robot (left) and a touch-screen terminal for inserting credit card, entering refilling order and printing (right). (From Leondes, C.T., *Mechatronic Systems Techniques and Applications,* Vol. 2, Gordon & Breach, Amsterdam, 2000. With permission.)

Underneath the refueling station, the robot moves into the initial position. It emerges from the opening in the refueling island and approaches the filler flap. The robot remains flexible when docked on, in other words, it can respond to vehicle movement even when subjected to a slight load.

Personal safety is enhanced by passive design measures and active optical sensors. During refueling, the area surrounding the robot is monitored for changes. Human movements, opening doors, etc. are detected during the docking-on process. The vehicle can be left at any time in an emergency, since nothing prevents the car door from opening. Safe access to the refueling island is guaranteed at all times. Figure 28.33 depicts a refilling station in operation since September 1995 at Fraunhofer IPA.

For more than 3 years, the robot has shown its reliability and robustness under even harsh conditions. The system is currently undergoing redesign to meet cost and operation requirements.

References

1. Angeles, J., *Fundamentals of Robotic Mechanical Systems. Theory, Methods and Algorithms,* Springer–Verlag, New York, 1997.
2. Arbib, M.A. and Liaw, J.S., Sensori-motor transformations in the world of frogs and robots, *Artif. Intelligence,* 72, 53, 1995.
3. Bogoni, L. and Bajcsy, R., Functionality investigation using a discrete event system approach, *Robotics and Autonomous Syst.*, 13, 173, 1994.
4. Cutkosky, M.R., On grasp choice, grasp models, and the design of hands for manufacturing tasks, *IEEE Trans. Robotics Automation,* 5, 269, 1989.
5. Engelberger, J.F., Robotics R&D in the U.S.A., *Proc. 24th Int. Conf. Ind. Robots*, Tokyo, 1993.
6. Leondes, C.T. (Ed.)*, Mechatronic System Techniques and Applications, Transportation and Vehicular Systems,* Vol. 2, Gordon and Breach, Amsterdam, 2000.
7. Hirose, S., A code of conduct for robots coexisting with human beings, *Robotics Autonomous Syst.*, 18, 101, 1996.
8. Iberall, T., Jackson, L., Labbe, L., and Zampano, R., Knowledge-based prehension: capturing human dexterity, *Int. Conf. Robotic Res.*, 82, 1988.
9. UN/ECE, International Federation of Robotics (IFR), *World Robotics 2000*, United Nations Economic Commission for Europe (UN/ECE), Geneva, Switzerland, 2000.
10. Kim, J.-O. and Koshla, P., Design of space shuttle tile servicing robot: an application of task-based kinematic design, 10, 648, 1994.
11. Masory, O., Wang, J., and Zhuang, H., On the accuracy of a Stewart platform. Part II: Kinematic calibration and compensation*, Proc. IEEE Int. Conf. Robotics Automation*, Atlanta, 1993.
12. Merlet, J.-P., Designing a parallel robot for a specific workspace, *Res. Rep.* 2527, 1995.
13. Morrow, D.J., Sensori-motor primitives for robot assembly skills*, Proc. IEEE Int. Conf. Robotics Automation*, Nagoya, 1995.
14. Murray, R.M., Li, Z., and Sastry, S.S., *A Mathematical Introduction to Robotic Manipulation*, CRC Press, Boca Raton, FL, 1993.
15. International Federation of Robotics, *Draft of the IFR Robot Statistics Documentation Package*, Revision 1, 1997.
16. Roth, B. and Mavroidis, C., Structural parameters which reduce the number of manipulator configurations, *ASME J. Mech. Design*, 116, 3, 1994.
17. Schraft, R.D., Degenhart, E., and Hägele, M., New robot application in production and service, *Proc. 1993 IEEE/Tsukuba Int. Workshop Adv. Robotics*, AIST Tsukuba Research Center, Tsukuba, Japan, 1993.
18. Schraft, R.D. and Hägele, M., Methods and tools for an efficient design of service robot applications, *Proc. 26th ISIR*, Singapore, 1995.
19. Schraft, R.D., Hägele, M., and Volz, H., Service robots: the appropriate level of automation and the role of users — operators in the task execution, *Proc. 2nd Fraunhofer IPA Technologie Forum F 17*, Stuttgart, Germany, 1996.
20. Schraft, R.D., Hägele, M., Heni, M., and Seid, R., *Mechatronic system techniques for robots for service applications*, in Leondes, C.T. (Ed.)*, Mechatronic System Techniques and Applications, Transportation and Vehicular Systems,* Vol. 2, Gordon and Breach, Amsterdam, 309, 2000.
21. Wang, J. and Masory, O., On the accuracy of a Stewart platform. Part I: The effect of manufacturing tolerances, *Proc. IEEE Int. Conf. Robotics Automation*, Atlanta, 1993.
22. Warnecke, H-J., Schraft, R.D., Hägele, M., Barth, O., and Schmierer, G., Manipulator Design in *Handbook of Industrial Robotics,* Nof, S. Y., Ed., John Wiley & Sons, New York, 42, 1999.