MANIPULATORS

FUNCTIONS AND MECHANISMS OF MANIPULATORS

Manipulators and Tasks

A manipulator is defined as a mechanical system that executes meaningful tasks by manual control, automatic control, or a combination of both. From that viewpoint, most conventional robots fall in the category of manipulators.

The tasks which the manipulator is commanded to perform can be diverse, e.g., performing hazardous tasks that humans cannot do, simply imitating human behavior, and performing tasks that humans can perform, but much more efficiently and with much improved reliability. We exclude manipulators, such as those that merely imitate human motions, those that function in special environments, e.g., underwater, space, vacuum, and so on, and those used for entertainment. Therefore we focus on manipulators that are actually used for practical task execution.

In a broad sense, manipulators that perform meaningful tasks in the domain of production activities, range widely in variety, as shown in Fig. 1. The main correspondences of those examples with tasks performed are as follows (Fig. 2):

1. Hydraulic excavator. A construction machine is not usually dealt with as a manipulator. A hydraulic excavator, however, is an exception. An excavator is one of the most representative construction machines which is mainly used to excavate earth [Fig. 2(a)]. It is also used to crush rocks, to grab timbers with a special attachment, and to transfer objects.
2. Machining center. The most representative machine tool used mainly for cutting metals [Fig. 2(b)]. When the attachment tool is replaced to cope with a required process, various operations can be carried out by replacing at least several tens of tools.
3. Multijoint articulated robot. Robots take part mostly in simple, repetitive motions with improved efficiency and reasonable accuracy. The main tasks involved in such motions are changing the position and the orientation of an object, that is, machine parts, materials, electronic components, and so on. These motions consist of a series of elementary motions, such as grasping [Fig. 2(c)], releasing, transferring, changing configuration, etc. The articulated robot is also used widely for painting [Fig. 2(e)] and welding [Fig. 2(f)] mostly in the automobile industry.
4. Industrial orthogonal robot. This type of robot is mainly used for assembly tasks in manufacturing whose typical motions include accurate positioning and insertion of mating parts [Fig. 2(d)].
5. Self-propelled mobile vehicle. This robot distributes and collects many parts and products to and from different work cells in a factory [Fig. 2(g)]. It performs elementary motions, such as loading, unloading, and transferring. There are cases where these loading and unloading motions are undertaken separately by a manipulator associated with each respective work cell.

Functions of a Manipulator and Their Constraints

Generally when designing a new product, we first determine the desired functions and then elaborate them in the order of functions, mechanisms, and structure (construction) while satisfying different constraints to which the product is subject (1). This stepwise elaboration process can be applied to the design of a specific mechanical device and also to the design of larger more abstract systems. Therefore, we describe those functions required of the manipulator from the viewpoint of theoretical design, those mechanisms used to realize respective elementary functions, and the design constraints associated with the functions.

As previously mentioned, various manipulators perform a variety of tasks, but common to all these tasks is that each manipulator generates relative motions between the work tool (end effector) and the subject item to be worked or between the item gripped and other subjects. In other words, this is the sole function of the manipulator. And, incidental thereto, the realization of motion, the conveyance of force, the transmission of information and transfer of materials, are required as functions, although they are lower functions. The

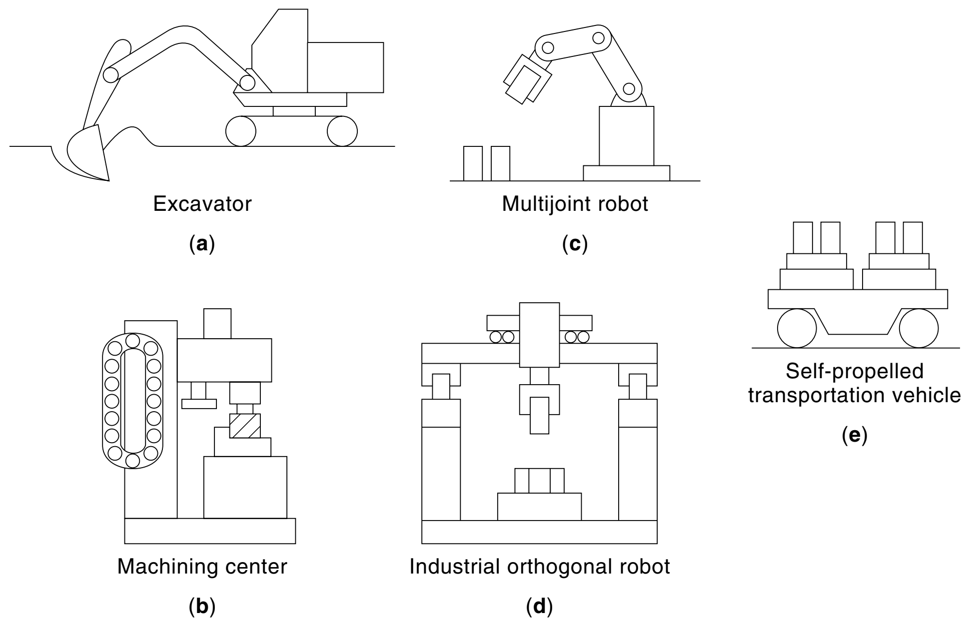


Figure 1. Manipulators working in different production fields.

mechanisms to realize these functions are explained in detail in the next section.

A very important function usually overlooked or underestimated when a manipulator is designed is the so-called "fail-safe function" that aims to avoid catastrophic destruction of the system in an unexpected situation. This function is better realized by using a structural device, not by relying on a software-based emergency handling procedure. At present, no manipulator sufficiently meets fail-safe need. However, it is strongly suggested that this function be given higher precedence when designing manipulators in the future.

To realize the desired functions, it is necessary to approach design from the viewpoints of both hardware (mechanism/construction) and software (control), but as software is discussed in other sections of this encyclopedia, this section deals mainly with mechanisms.

When looking at the specific composition of a manipulator (Fig. 1), there are common items for many of the different manipulators regardless of which tasks they are intended to perform. As shown in Fig. 3, whatever the physical structure and configuration may be, attached tools or workpieces exert an action on another tool or workpiece, and the manipulator is the device that performs the action and establishes physical interactions between the two objects. As shown in Fig. 3(a), the manipulator has a base, a drive source, an actuator with a transmission mechanism, an arm, a sensor, and a gripping

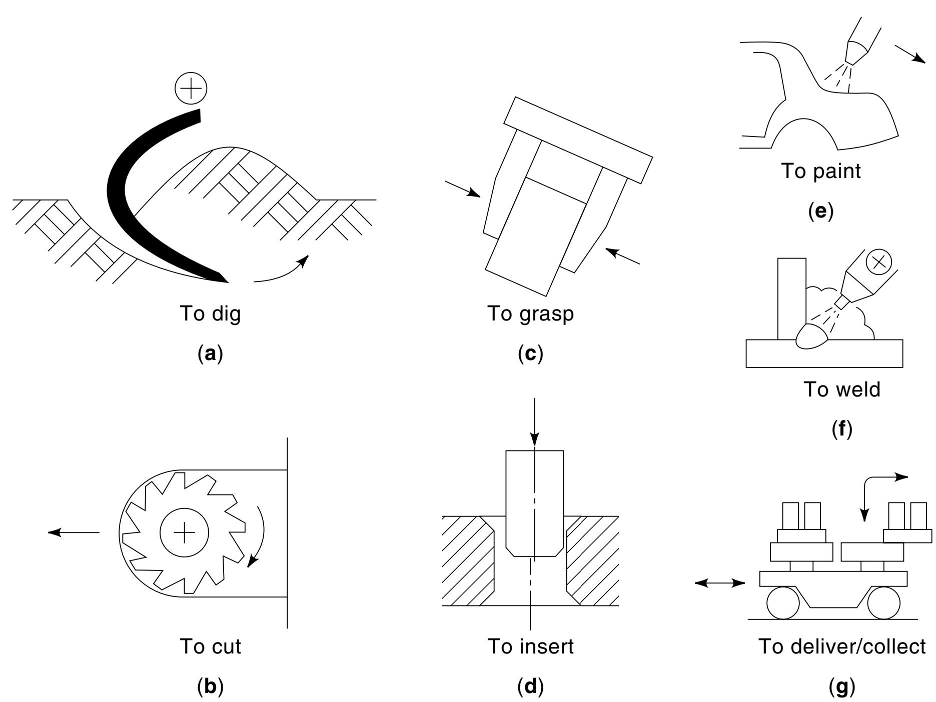


Figure 2. Various tasks which manipulators execute.

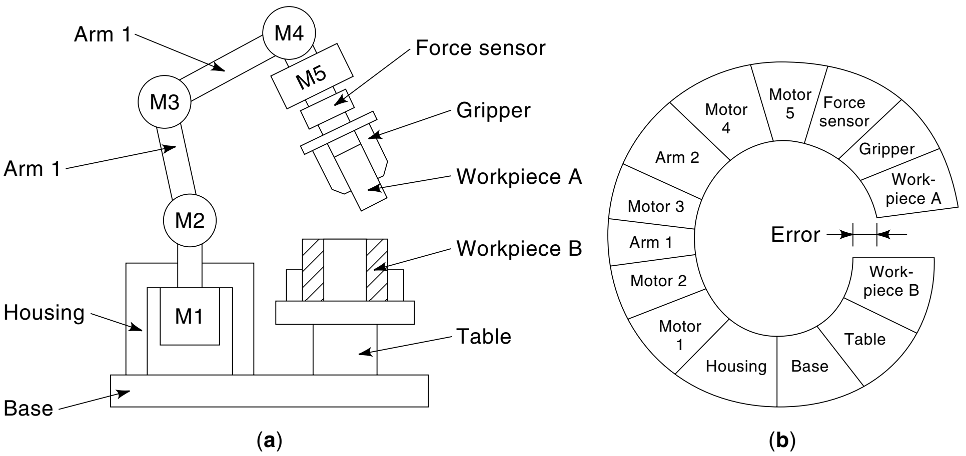


Figure 3. Basic structure of a manipulator (a) and C-circle of a manipulator (b).

tool connected nearly in series and forming one structural body. If the whole body is abstracted, the entire structure forms a C-shape beginning from the tools or the workpiece and reaching to the other end which is the object to be worked. This abstraction is called the C-circle of a manipulator (hereafter abbreviated as C-circle). The C-circle is the most important factor that determines a task's accuracy (in other words task tolerance) and required execution time, which are the fundamental performance criteria of a manipulator.

Constraints related to the design of a manipulator include operability, manipulability, maintainability, cost, etc., and the constraints on the manipulator itself are weight, operational accuracy, motion characteristics (rise time, settling time), tact time, etc. (Fig. 4). Of these, constraints on operability are limited by the mechanical characteristics of the hardware and the control characteristics of the software. These mechanical characteristics are coped with by considering rigidity, shape, resonance, thermal deformation, etc., of the C-circle as a whole. For example, although the harmonic drive reduction gear widely used in robots is light, small, and convenient, it essentially lessens the rigidity of the C-circle and therefore is recommended most where there is a strong demand for high accuracy and high-speed operation. Although there are several difficulties from the design viewpoint, there is no other approach but to simplify the C-circle using a direct-drive motor and improving rigidity.

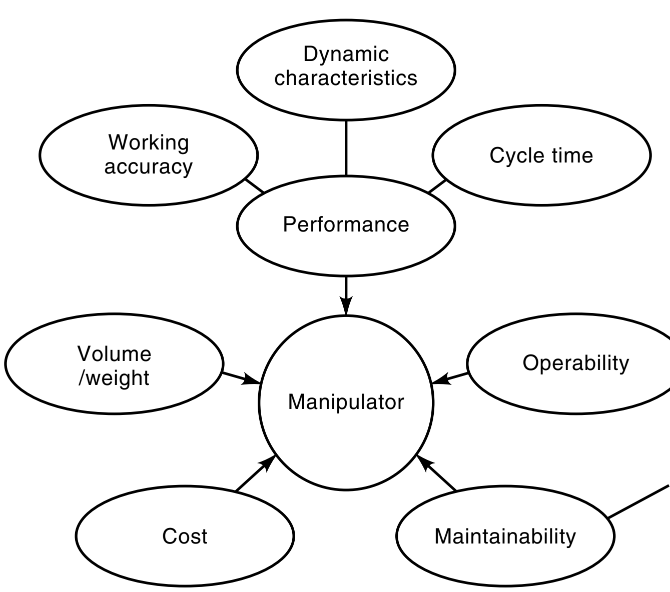


Figure 4. Constraints imposed on a manipulator.

Mechanism To Materialize Functions

An actual manipulator is an integration of mechanisms corresponding to a set of elementary functions designed to fulfill desired specifications under the aforesaid constraints. The mechanisms involved can be diverse, depending on their use. The next section in this article explains the mechanisms used for a manipulator in normal environments in terms of dimensions, and the section following explains the use of a manipulator in the microworld. Here we introduce some mechanisms that are considered essential to the future development of robots and manipulators although the world of robotics under present conditions does not pay much attention.

Fail-Safe Mechanism. In the process of operating a manipulator, if it collides with human operators or other machines, a part of the manipulator or the other machine may be damaged due to the excessive force of the collision, or it may lead to a fatal accident at worst. In the conventional design of a robot, a sensor-based control system is used to sense the failure and take appropriate action before a serious problem occurs. But the desired functions often cannot be fulfilled because of the time lag in the control system. Therefore, it is preferable that the fail-safe mechanism be realized by part of the structure, which should have the characteristics shown in Fig. 5(a). To produce this, for example, two pairs of springs and stoppers as shown in Fig. 5(b) are combined in tandem (2).

Variable Compliance Mechanism. The manipulator that fulfills desired functions by its motions necessarily forms a C circle. For this reason, it becomes difficult to fulfill two desired functions, a large work space and high positioning accuracy, at the same time. To solve this problem, a function is called for that changes the rigidity of individual parts and joints, which compose the C-circle. For this purpose, for example, increasing the apparent geometrical moment of inertia

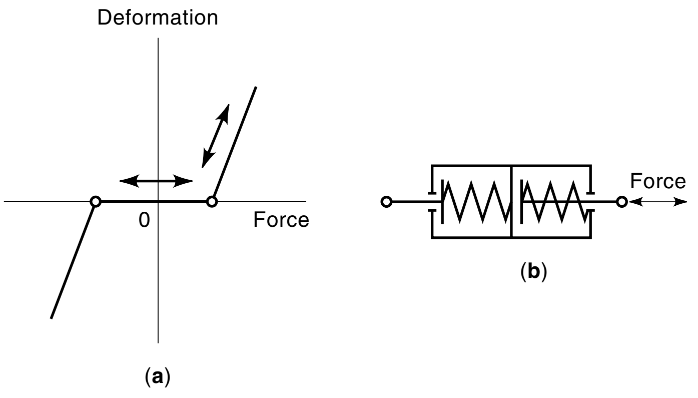


Figure 5. Fail-safe mechanism: (a) force-deformation characteristic of fail-safe mechanism; (b) concrete example of fail-safe mechanism realized by series connection of spring/stopper couples.

(Fig. 6) by adsorption with an electromagnetic sheet and fixation of joints are effective.

Macro/Micro Structure. To substantiate the same desired functions mentioned previously, segmentation of role sharing of the moving parts (actuator, arm, etc.) is effective, that is, combining a coarse movement mechanism and a fine movement mechanism, as in the case of a direct-drive motor and a piezo actuator, to produce a large work space and high positioning accuracy. Even here, a combination of actuators alone is not sufficient, and at least a mechanism for fixing the interface between the two should be incorporated in combination to produce operations (Fig. 7).

Local C-Circle Structure. When fine motion tasks and small force operations are to be performed at the tip of the arm, it is difficult to maintain the relative position between tools and gripping parts and the object parts, no matter how accurately position control is performed at the base of the arm or how rigidly the arm and the actuator are raised. Particularly where reactive force is received by operations, deviations in position and orientation are caused by the reactive force no matter how small. Although a controller is often used to increase the apparent rigidity of the C-circle in solving the problem, its contribution is not so significant. Under such circumstances, incorporating small local C-circles in parallel with the large C-circle is extremely effective (Fig. 8).

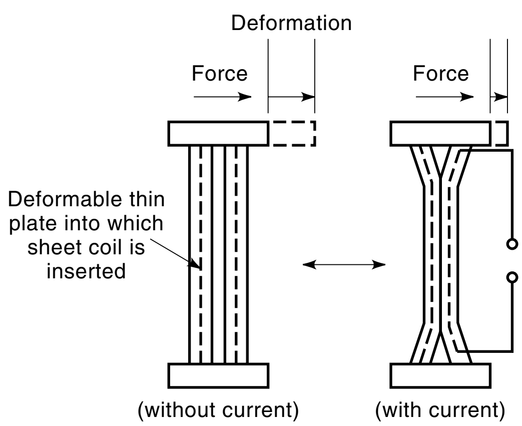


Figure 6. Variable compliance mechanism.

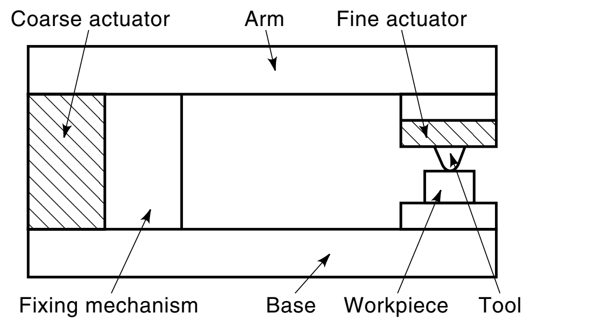


Figure 7. Realization of fine operation through piggyback structure.

Junction. When tasks performed by one manipulator are diverse, a variety of end effectors is necessary. In this case, more than a simple mechanical connection/disconnection is required at the junction between the manipulator and end effectors. What should be exchanged through the junction includes mechanical relative position, transmission of force and torque, transmission of information, and transfer of substances, such as cutting fluid, air, and gas. The interface carries out secure transmission and transfer through the connector ports. As of now, the most serious technical difficulty resides with the transmission of information. Sensory information about the interaction between the end effector (gripper or tool) and the object can be transmitted to the manipulator, but in many cases the signal level is very low. It is also common to have actuators on the tool side which provide necessary motion at the tool end. Therefore, sensor signals and also energy must be transferred from one end to the other (Fig. 9). An example of an application to manipulators is schematized in Fig. 10. In the future, technological efforts should be made for more secure and efficient transmission. For this purpose, magnetic and electromagnetic coupling are promis-

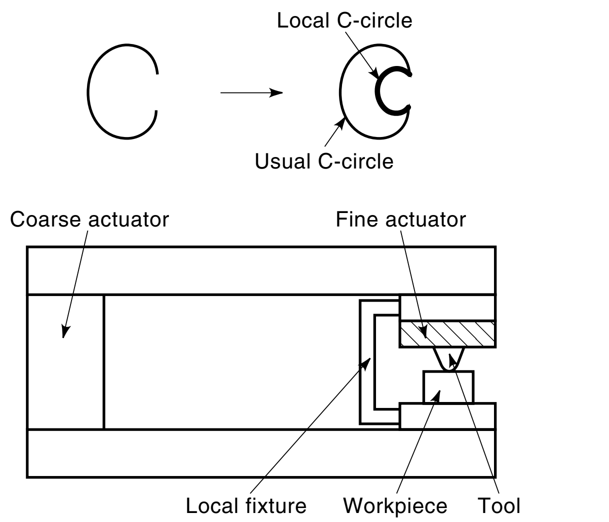


Figure 8. Improvement of working accuracy by local C-circle structure.

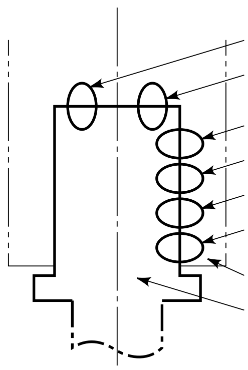


Figure 9. Basic performance required for smart connectors of a manipulator.

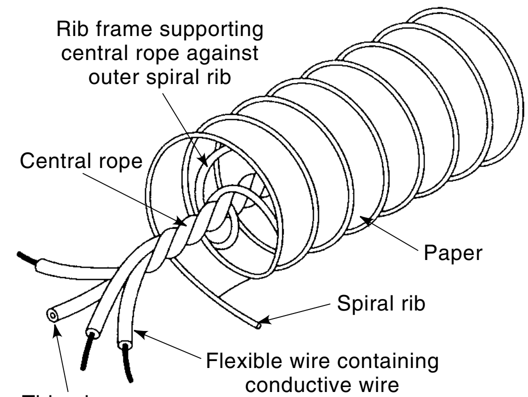


Figure 11. Example of an arm structure which does not make humans afraid.

ing because they are not susceptible to contamination at the joint surface (3).

Soft Appearance. Although functions called for by the industrial manipulators are as described previously, manipulators in the future will, inevitably, have more occasion to interact with humans. Therefore a tender appearance which gives human users a sense of ease, but not a sense of fear or anxiety, will become vitally important. Humans will always remain the master over manipulators under any circumstances and they require that the manipulators not be in a position to make them afraid or to inflict injury. Manipulators that physically interact with humans should be weaker than humans. For this reason, manipulators must be soft and light enough to give humans a feeling of ease, but nonetheless rigid enough to execute given tasks. The functions considered contradictory in the engineering sense will be justified when higher precedence is given to safety issues. To fulfill the desired functions, adopting special structures and materials such as very light synthesized materials or paper materials, may be useful (Fig. 11).

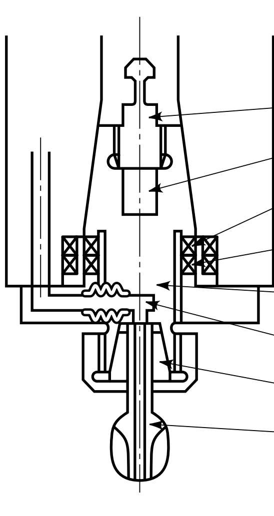


Figure 10. Example of the smart connector.

COMPOSITION OF NORMAL SIZE MANIPULATORS

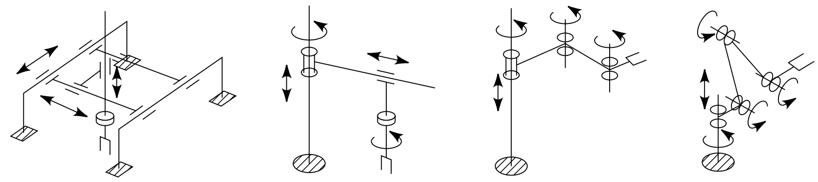
Hardware Design of Manipulators

Task Elements Called for by Manipulator. A programmable, automatically controlled, multijoint manipulator is called a robot in industry. This section introduces this kind of robotic manipulator, which we call a normal-size manipulator whereas a small-size robot, termed a micromanipulator, is treated later. There are many introductory books about robotics in general (4–9) that deal mainly with three major aspects of robotics, kinematics, dynamics, and control. This section views manipulators from a design perspective.

Industrial production processes that involve robots are divided mainly into three processes, such as assembling informational equipment, welding automobiles, and handling injection parts. In Japan particularly, these three large production processes account for approximately 70% of all processes in which robots are used. Analysis of specific tasks performed by the robots in these three processes tells us what kinds of task elements are required of manipulators. Two kinds of tasks appear commonly, picking and placing objects and tracing object surfaces.

Although robots are used in processes other than these three, a careful task analysis reveals that many of them consist of a series of the two previously mentioned task elements. There is only a minor difference in the overall task objectives, such as in heavy-load lifting or painting. These three processes are widely used because the tasks performed are suitable for a robot and because developing task-dependent robots dedicated to a specific task is too costly, resulting in increased employment of general-purpose robots.

Next, we shall examine the desired operations of robots in the future. It may safely be said that current production processes that can benefit from the investment in robots have already been developed almost to their fullest extent. Processes expected in the next generation have been spreading out of manufacturing industry, for example, operations in hazardous environments (e.g., nuclear reactor, minefield, active volcano, site of disaster), operations to care for the physically handicapped, operations where humans cannot see with the naked eye or cannot touch with fingers because the ob-



Type	Orthogonal coordinates	Cylindrical coordinates	Horizontal multijoint	Vertical multijoint
Mechanism				
Freedoms of motion	3–5	4–5	3–4	5–6
Mass of work	1–5 kg	5–100 kg	1–50 kg	5–200 kg
Accuracy of positioning	±0.2 mm	±0.1 mm	±0.05 mm	±0.3 mm

Figure 12. Specifications of different robotic structures.

jects are extremely small or are inside the human body (e.g., dissection of a single cell or keyhole surgery), and operations performed in an environment of clean air, vacuum, or a reducing atmosphere, where humans cannot share the environment.

Within their environment all of these robots more or less mimic operations performed by humans in the normal world. Similarly, when task elements involved in these operations are considered, in fact the two major task elements previously mentioned account for the greater part. For example, the task element specially called for by a nursing manipulator is to lift physically handicapped persons and move them, and the microsurgery manipulator is called on to move surgery tools as if tracing the affected part. Of course constraints associated with the task elements differ from those for industrial manipulator presently in use. Softness and tenderness, so that the handicapped person is not afraid of nursing manipulator, preciseness that allows highly accurate movement, and softness that leaves the affected part minimally invaded by the microsurgery manipulator are required.

Mechanism of Normal-Size Manipulators. To accomplish these two task elements, the manipulator has to undergo spatial movements within the given work space. As an example of its mechanism, let us introduce the mechanism of an industrial manipulator in Fig. 12.

Four mechanisms are shown in the figure, but choices of mechanisms are made by analyzing task elements. Three conditions are of primary concern: required degree of freedom of motion, weight of objects, and required accuracy of positioning. In the aforementioned three processes as examples, two require high positioning accuracy although the object is relatively light. An orthogonal coordinate type and horizontal multijoint type (SCARA) for assemblying informational equipment (e.g., circuit board) and an orthogonal coordinate type and cylinder coordinate type for handling of injection parts are used, respectively. On the other hand, when the task requires tracing curved surfaces, such as welding automobile frames, an articulated multijoint type is used. The degree of freedom of a respective mechanism is either rotational or prismatic. When rotation is used for a degree of freedom, the configuration of tools can be arbitrarily set. Although the rotational rate can be very fast, the rigidity of the actuator is rather low, hence positioning accuracy is worsened. On the other hand, when translational motion is used, both the rigidity of the actuator and the accuracy of positioning improve whereas the tool orientation becomes fixed and the tool motion is rather slow.

Some constraints should be relaxed to overcome these shortcomings. First to be tackled is the rigidity of the driving system. In the case of a robot manipulator, generally, no substantial bending of arms, no distortion of joints nor deformation of structure occurs unless a flexible structure is intentionally used. What is crucial is the deformation and chattering of the drive mechanism caused by external forces and moments from actuators, couplings, gear trains, etc. Next, because the motion of tools is generally constrained by acceleration rather than velocity, the acceleration to which the drive system is subjected can be considered a constraint. To circumvent this constraint, there is no other way but to make the mass of moving parts including the object lighter to increase rigidity to suppress unwanted vibration, or to make the drive power of the actuator larger, although positioning accuracy is governed by how well thermal expansion and inertial force are compensated for by control. The more cumbersome problem would be the thermal expansion of the structure because the inertial force generally is repeatable and can be compensated for rather easily if the weight of the object and the dynamics of the drive system are estimated. However, the thermal expansion (determined by the average temperature of the whole and also by the internal temperature distribution) is hard to compensate for because the interior temperature of the structure generally cannot be measured. The final constraint is the limitation of tool configuration. In many cases this can be resolved quickly if design change on the side of the object is accommodated. The constraint in this case is the design of the object, which requires the flexibility and willingness of the designer to accept modification of objects.

The next section describes how these constraints are overcome.

Design Constraints on Manipulators. Four kinds of constraints for designing manipulators have been mentioned: rigidity of the drive system, acceleration of the drive system, thermal expansion, and design modification of the object. These are reviewed in depth in this section.

First we discuss the rigidity of the drive system. For the manipulator to trace a trajectory under the influence of external forces and inertial force, the more rigid the actuator becomes, the better the accuracy achieved. Ideally speaking, a robot with position feedback should retain infinite rigidity. In other words the same position should be maintained whether the robot is pushed or pulled from its extremities. At least the resonance frequency should be approximately on the order of several hundred Hz at the tip of tool. However, because the position sensor does not provide the precise position of the object, things do not work as expected in reality. For example, when the position is sensed by an encoder attached to the motor and drives the tools via reduction gears, like a harmonic drive, the resonance frequency at the end of the tools drastically decreases, for example, to 10 Hz.

However, as far as actual task executions are concerned, in many cases, especially in an emergency, the smaller the rigidity, the better the performance. Particularly, when an object placed at inaccurate position is to be handled, for example, inserting a peg in a hole or grasping a ball with the gripper, it can be resolved by highly precise servocontrol or by no position feedback at all, if artificial compliance is employed. When dealing with unexpected sudden moves or collisions with its environment, one method suggested is to incorporate a mechanical fuse in the manipulator which absorbs collision impact or unwanted excessive force to keep the damage minimal. The margin of such misoperation is immensely narrowed when humans are nursed or operated on by a manipulator. Under such circumstances it is desirable to insert a mechanical element with variable rigidity which automatically becomes softer in an emergency or makes the exterior skin of the manipulator softer like a car air bag when a collision occurs or an excess force is exerted.

Second we discuss the acceleration of the drive system. As long as the actuator size is comparable to a human, the positioning accuracy is reduced rather easily, that is, smaller than 0.1 mm readily using any actuator unless too sudden a start or a stop is involved. However, as the acceleration exceeds 2*g*, vibration remains even after arrival at the target position, arms get twisted and the posture of tools changes, and the driving torque becomes insufficient, causing the motor to generate excessive heat. Recently, a direct-drive motors to increase the acceleration of rotation and linear motors to increase the acceleration of translation have frequently been employed. The latter, especially, makes it possible to attain an acceleration as high as 10*g*, but heat generation also becomes significant requiring compensation for thermal deformation, the next issue to be discussed.

Third we discuss thermal expansion of the structure. If an arm one meter long is made of aluminum and its temperature is raised by one degree, then the thermal expansion at the tip is 0.2 mm. In reality, the temperature rise is easily several tens of degrees when the actuator is not appropriately cooled or when heat is generated by a welding torch or heat-emitting device. Then accuracy of positioning is even worsened, for example, by 0.1 mm. Thermal expansion is often forgotten by many robot designers. In manufacturing semiconductors and precision machining, however, compensation for thermal expansion is unavoidable. An easy solution to the problem is to keep the ambient temperature constant because it is quite difficult to achieve accurate compensation.

With the rapid advance of different kinds of sensors, including image sensors, force sensors, and noncontact position sensors, which use laser, eddy current, electrostatic capacity, and so on, the relative position between the end effectors (tools) and the object can be accurately measured. This allows accomplishing tasks even when the accurate, absolute position of the tip with respect to the distal base is not known. In the future, a combination of these sensors and fine motion mechanisms mounted on the tool, for example, piezoelectric or friction-drive, will be subject to frequent use to compensate for relative positional error at high speed.

The last issue is design modification of the object. To simplify the motion of a manipulator, it is often beneficial from the viewpoint of task execution to change the design of the object to a simpler one. For example, the shape of an object in which parts are inserted from more than one direction may be changed so that all parts are accessed from one direction, thus greatly simplifying the assembly task. Two parallel surfaces may be fabricated in the object with which handling of the object can be made secure and easier, or fabricating a large chamfer on the edge of the pin to be inserted produces self-aligning capability and makes an insertion task easier. In addition, although this may be a rather extreme example, assembly of two different parts which requires a robot may be replaced by a design change which integrates the two parts as one part. This kind of decision should be made carefully by considering several factors: cost for redesigning, necessary change in manufacturing process, matching with other parts, and so on.

Robot Hand

It was said a while ago that a robot is only as good as its hand or end effector. Although the situation may be slightly different after the emergence of a variety of locomotive mechanisms, such as legs, wheels, crawlers and so on, still many tasks largely depend on the end effector and any tool that actually performs the tasks. Nowadays the robot hand has been diversified in wide application of robotic systems from deep underwater to outer space, from construction machinery to microsurgery, from handling of toxic chemicals or explosives to tender care of elder people or handicapped. There is, however, no doubt that the robot hand plays a vital role in every one of the applications.

Generally speaking, the arm, wrist, and legs are versatile because they are used primarily for positioning the hand and any tool that it carries. The hand, on the other hand, is usually task-specific. The hand for one application is unlikely to be useful for another because most robot hands and end effectors are designed on an ad hoc basis to perform specific tasks with specific parts. Although the vast majority of hands are simple, grippers, pincers, tongs, or in some cases remote compliance devices, some applications may need more dexterity and versatility than these conventional hands can deliver. A multifingered hand offers some solutions to the problem. An excellent review of multifingered hands and their related issues can be seen in (10). One recent example of a multifingered hand, called the Barrett hand, is shown in Fig. 13.

This section gives a general description of robot hands from the practical point of view rather than introducing the state of the art of the field. In industrial applications, robot hands do not necessarily have fingers. As a matter of fact,

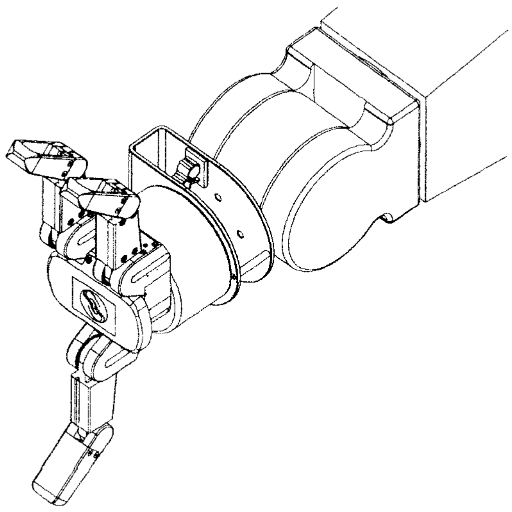


Figure 13. Three-fingered robot hand. Reprinted with permission of Barrett Technology Inc.

those which utilize magnetic force or vacuum suction force do not require fingers which may be added to prevent the object from falling off. Here we focus on grippers which have fingers (typically two or three).

When a robot hand is designed or selected, the following points need to be considered:

- Gripping force and workpiece weight
- Robot load capacity
- Power source
- Work space
- Environmental conditions

These five points are discussed in detail here.

1. Relation of gripping force and workpiece weight: It is suggested that the gripping force be about 5 to 20 times the workpiece weight. Its value may be affected by the shape of the finger attachment, the friction condition of the contact surface, the gripping method, and the transfer speed. The faster the transfer speed, the larger the gripping force required. Typical gripping methods are illustrated in Fig. 14. In the top figure, frictional force is induced by the rubber pad mounted on the attachment surface whose frictional coefficient is about 0.5 as opposed to 0.1 to 0.2 for steel material. The bottom figure has a hook for drop prevention. In case of low transfer speed without vibration or shock, for example, less than 0.1 m/s, the gripping force is chosen in the range of 5 to 10 times the workpiece weight. On the other hand, if the workpiece is subjected to high acting speed, vibration, or shock (high acceleration), for example, more than 1 m/s, or if the center of gravity of the workpiece is distant from the gripping point, a gripping force more than 20 times as large as the workpiece weight is required.
2. Robot load capacity: The total weight of hand, workpiece, mounting plate, and finger attachment must be smaller than the payload capacity of the manipulator. Attention should also be paid to the definition of the payload capacity, for example, worst case scenario or other specific configuration.
3. Power source: Most conventional robot hands use an electrical, pneumatic, or hydraulic power source. Each method has its pros and cons. Electric motors, such as dc motors or step motors, are commonly used to drive a robot hand and the joints of a manipulator because they are easy to use and are a good compromise of response, accuracy, and cost. Hydraulic motors are common in applications requiring large power, such as construction machinery, for lifting heavy objects or crushing rocks. One of the attractive features of the hydraulic drive is that it runs more smoothly at low speed than electric motors. However, a hydraulic drive may exhibit dynamic behavior that is quite oscillatory. The main drawback is possible leaks in the closed oil-flow system. Pneumatic drive systems are quite effective when a large force is not required and a simple open/close operation suffices. They also do not require return circuits as hydraulic drive systems do. The main limitations are low positioning accuracy, low rigidity, and exhaust noise.

Another concern closely related with choosing the power source is cables or hoses. Any cables or hoses

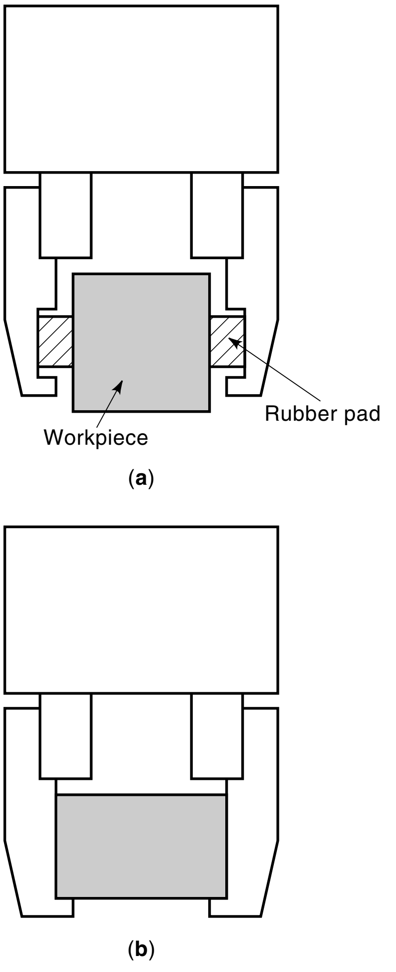


Figure 14. Examples of the finger attachment of a robot hand: (a) rubber pad mounted on the finger attachment; (b) hook on the finger tip for drop prevention.

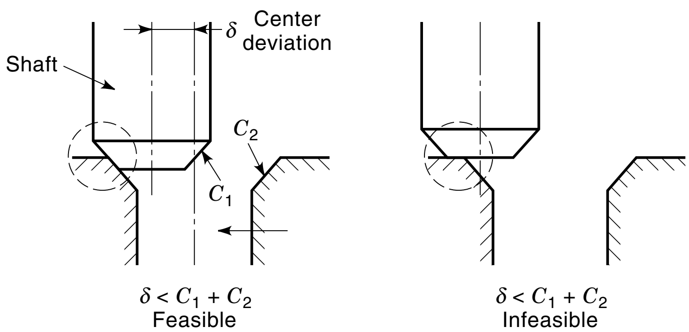


Figure 15. Feasibility of an insertion task.

routed from the base to the end tip of a manipulator experience enormous flexure. An inappropriate choice may cause an early breakdown of the power system or severe hindrance to the smooth operation of the manipulator. Also, no excessive force should be exerted on connectors, cables, or hoses.

4. Work space: If picking and placing a workpiece is the task to be performed by the hand, an appropriate work space has to be provided for each action. The hand needs a certain space for approaching the work piece, and it also requires a space for picking and releasing it. The detection method for finger opening, closing, and catching the workpiece is also related to work space.
5. Environmental conditions: If a robot hand is used in a clean room, for eaxmple, handling semiconductor wafers or magnetic memory disks, special attention needs to be paid, especially to the power source, transmission mechanisms, and sealing mechanisms, so that no contamination is emitted from the hand. Other potential concerns include coolant, grinding dust, water, and ambient temperature.

Beside the points mentioned, there are peripheral technologies which are closely related to robot hands which are used widely in industrial applications.

- Automatic tool changer (or automatic hand changer): Unless the host robot is occupied with the same task, it is convenient to have a supply of different grippers and the ability to switch between them as tasks change. A robot arm exchanges grippers by using a turret or a tool changer. A turret is limited to switching between only two or three grippers whereas a tool changer handles a large number of grippers. In an automatic tool changer, each tool has a common mechanical interface through which the power source and the sensor signals are transmitted. Potential drawbacks of such tool changers are increased cycle time, reduced arm payload capacity, added expense, and reduced system reliability.
- Remote Center Compliance (11): For inserting a shaft into a hole, the relationship between the chamfers and the feasibility of the task is as illustrated in Fig. 15. The tolerable center deviation between the two parts is determined by the following equation (12).

$$\delta < C_1 + C_2 \qquad (1)$$

where δ is the center deviation and C_1 and C_2 are the chamfering dimensions of the shaft and the hole, respectively. If this equation is satisfied, then the shaft is passively guided into the hole by the chamfers. Otherwise, it is impossible to accomplish the insertion tasks unless the center deviation is actively compensated for until the equation is satisfied

Even when the equation is satisfied, some proximal part has to tolerate such an alignment motion of the parts. A Remote Center Compliance (RCC) device was specifically developed for this purpose (11). The device is equipped with two compliant elements. One allows lateral motions, and the other tolerates rotational motions about the tool tip. Its structure is schematized in Fig. 16(a). The device is often substituted by a simpler version of RCC which roughly realizes the lateral motions and the rotations [Fig. 16(b)].

This section concludes with pictures from more recent applications of parallel jaw grippers in agile robotic systems (Fig. 17).

Multiaxis Force Sensor

Object Manipulation and Force Sensing Information. In most cases, the robots that have become familiar for practical use up to the present are taught motions one by one, and the robots simply repeat them. In contrast, future robots will be self-supporting by taking in the information from outside, judging it, and acting. At that time, the intelligence that judges the information and the sensors that take in the information will play important roles.

Because robotic motions are diverse, we will consider the handling operations that become the center of motion, in other words, the handling of the object by the manipulator or the end effector attached thereto. What immediately comes to mind is the assembly robot in a factory production line, where object mechanical parts to be handled are hard and can be handled roughly. In the future, however, there will be soft or fragile, delicate objects or there will be the need to handle objects of unknown nature. In the cases of the nursing robot and the surgery robot, the objects are humans themselves.

What kind of processes are needed when an unknown object is to be handled? First of all, the position, size, and shape of the object must be estimated by visual inspection, followed by identification of the hardness or softness and contact condition with the object by touching it with fingers. Then by lifting it, the weight and the position of center of the gravity can be determined. In other words, humans grasp the characteristics of an object by using information derived from their sense of sight and by force sense (including tactile sensing) information from hands and arms. For fragile objects, force and tactile sensing become essential. Human hands are a highly complex and integrated system having many degrees of freedom and different sensing capabilities, which enables a very high level of dexterity and flexibility.

The functionality possessed by robotic hands still falls far short of that of human hands. However, those used in industrial applications are furnished with the minimal functions. Necessary information for handling the object can be obtained as visual information from a CCD camera and as force information from a force sensor attached to the manipulator or the

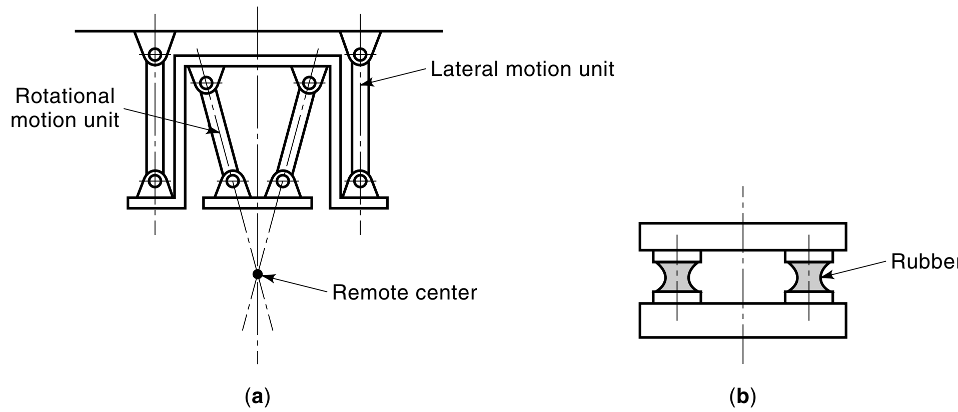


Figure 16. Remote center compliance (RCC): (a) remote center compliance (RCC); (b) quasi-RCC device.

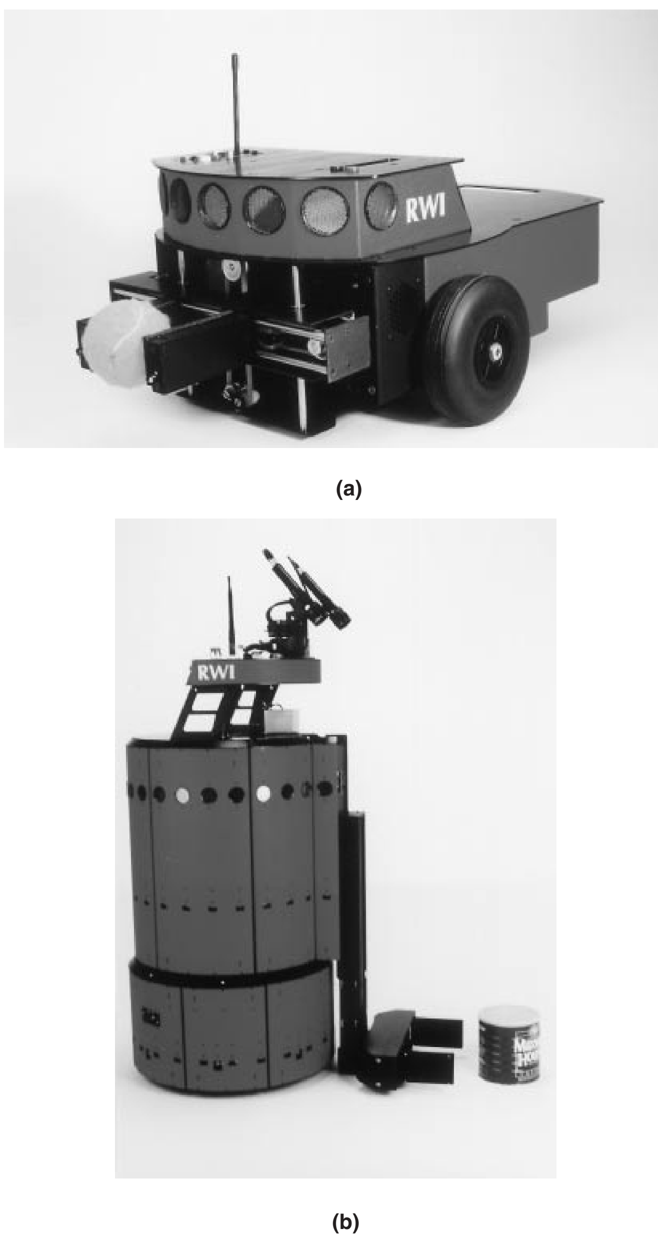


Figure 17. Robot hands in agile robotic systems: (a) wheeled mobile robot picking up a tennis ball. Reprinted with the permission of Real World Interface Inc. (b) visually guided mobile robot approaching a coffee can. Reprinted with the permission of Real World Interface Inc.

end effector. The former is explained in detail in other sections. The rest of this section describes force-sensing issues.

Force Sensing and Force Sensors. Force sensory information means information about forces and moments observed at the interface between the end effector and the object when performing handling tasks. These forces and moments are fully described by six components: forces in three orthogonal axes and moments around the same axes.

Based on the force information, a lot of useful information is obtained, such as contact point, contact force, object configuration, object shape, and so on. Knowing this allows us to perform considerably complicated operations with force information alone. Currently, however, robots are used merely for deburring mechanical parts or fitting mating parts, but in the future, force control will be an indispensable technology when handling more delicate objects.

The techniques of sensing forces and moments are roughly divided into two methods, one that uses a force sensor and one that does not. In the latter case, the load of the object is calculated from the driving torque of the motor that drives the manipulator joints or end effector. Specifically, a dynamic model is described, and the load is calculated as a disturbance from the difference between the actual motion and the nominal motion derived from the mathematical model. To obtain force sense information with high accuracy, however, it is preferable to employ a force sensor.

Now, what kind of sensing mechanism is used in force sensors? In machine tools, piezoelectric elements are frequently used as pick-up devices. This utilizes the fact that because of the piezoelectric effect an electric charge is induced when a force is applied. The piezoelectric element has advantages that it has high rigidity and therefore it does not reduce the rigidity of the original machining system. There are also disadvantages, such as a large sensor, arbitrary setting of sensitivity is difficult, potential leakage of electric charge gives trouble in long-term stability, integration of multiaxis sensing is difficult, and so on.

The force sensors widely used for robotic applications use strain gauges as sensing elements. A strain gauge is placed at a position where a specific force or moment is effectively measured. The less cross talk, the better the sensor. Because the sensing resolution is inversely proportional to structural rigidity, increasing the sensitivity leads to a decrease in rigidity. Therefore, it is important to choose a force sensor to execute desired tasks which is sensitive and is also rigid. The major advantages of strain gauges are that they can be made

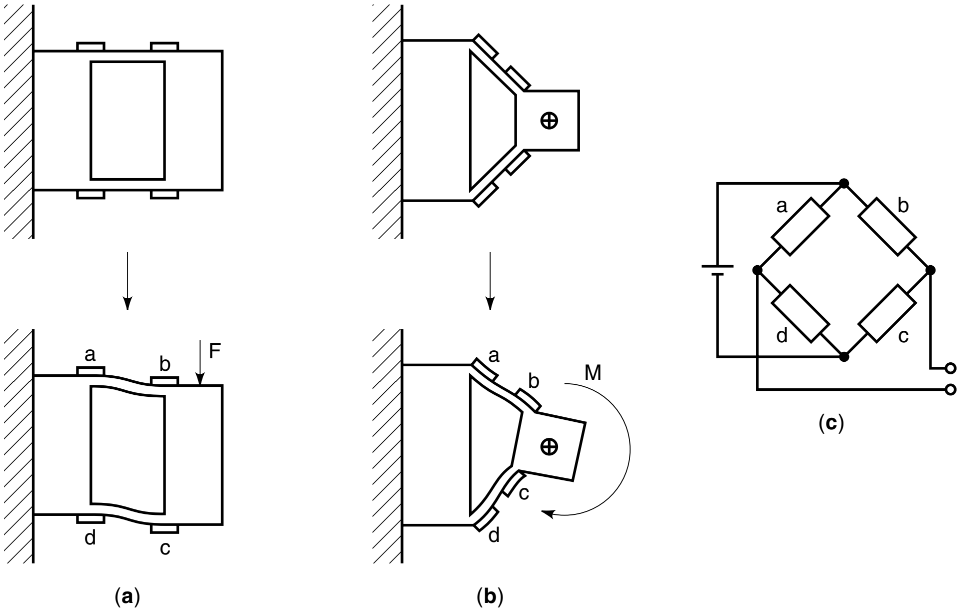


Figure 18. Sensing force and moment with parallel plates and radial plates: (a) sensing force with parallel-plate structure; (b) sensing moment with radial-plate structure; (c) bridge circuit with strain gauges.

smaller, sensitivity can be chosen at one's disposal, the operation is stable, integration of multiple axes is easy, and they are generally much cheaper than the piezoelectric type.

Multiaxis Force Sensor Using Parallel-Plate Structure. In this subsection, a multiaxis force sensor which utilizes a parallel-plate structure and strain gauge is introduced as a practical example. Figure 18 shows the schematics of a parallel-plate structure and a radial-plate structure that is a variation of the parallel-plate structure. The parallel-plate structure, Fig. 18(a), has its movable part connected to the fixed part with a pair of thin parallel plates. As a force is exerted on the movable part, it exhibits a translational displacement in parallel with the fixed part. The elastic strain on the plate surface is measured by the strain gauge. By forming a Wheatstone bridge, the force is detected as an electric signal. The characteristics of the parallel-plate structure are that its major displacement is permitted only in one direction and its high rigidity in the other directions yields an excellent sensing separativity. Also the sensitivity can be arbitrarily chosen according to the design of the parallel plate. The radial plate shown in Fig. 18(b) is employed to measure a moment applied to the movable part.

Figure 19 shows examples of variations and combinations of parallel-plate and radial-plate structures. Combination of these can provide many different types of force sensors. Figure 20 shows a six-axis force sensor composed of three sets of the parallel plates and three sets of radial plates. In the construction the parallel plate is used for force measurement, and the radial plate is used for moment measurement. Six linearly independent force components have to be generated from the six sensing signals. Although the original signals contain some level of cross-talk signals, applying a decoupling matrix to the original signals suppresses such cross talk to as little as approximately 0.1%. Figure 20 shows a ring-shaped, six-axis force sensor composed of a parallel-plate structure alone (13). It has twelve detection parts from which the six components, three forces and three moments are computed. A force sensor is typically installed near an operational end, for example, the wrist of a robot, and, with this design, the hollow center is utilized for transmitting electrical power and sensor signals from the arm to the end effector or vice versa.

Figure 21 illustrates the primary and the secondary modes of deformation in parallel-plate structures. By using the sec-

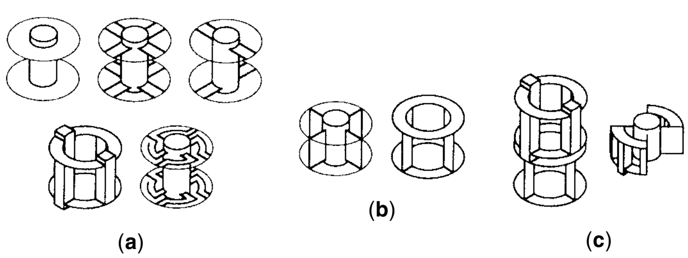


Figure 19. Examples of parallel-plate and radial-plate structures: (a) parallel-plate structure; (b) radial-plate structure; (c) combination.

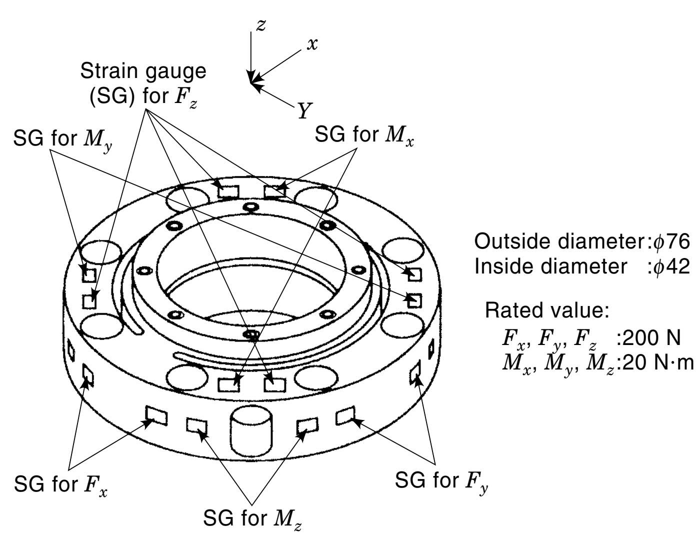


Figure 20. Structure of a ring-shaped, six-axis, force sensor.

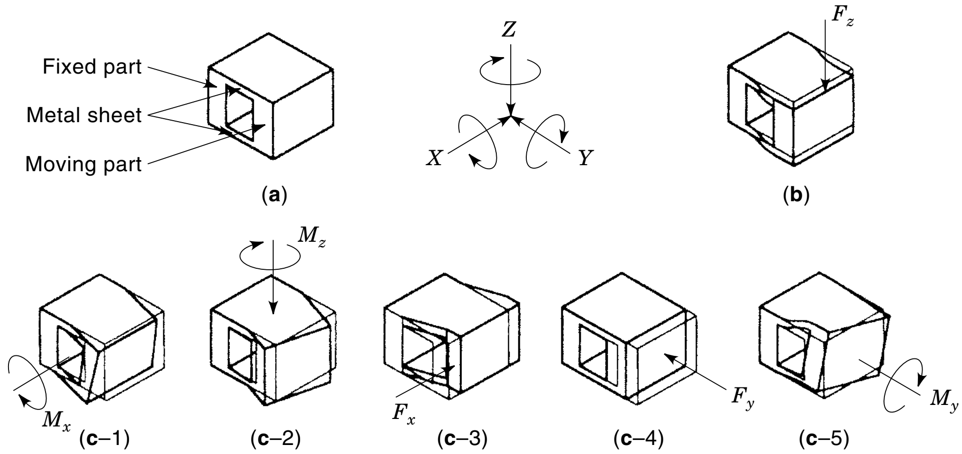


Figure 21. Sensing directions and corresponding deformation modes: (a) structure; (b) primary deformation; (c) secondary deformation.

ondary mode, a six-axis force sensor of a simpler construction can be composed (14). Figure 22 depicts a cylindrical six-axis force sensor using the secondary mode for sensing moments. This sensor can also be used as it is as a finger of a robotic hand.

Micromanipulation

Description of Operations. Micromanipulation (hereinafter to be called microoperation) includes assembling microparts and surgical operations conducted under an optical microscope or an electron microscope. Although the size of the manipulator is large, operations performed in handling the micro-objects, are called microoperations. The term microoperation is not affected by the size of the manipulator involved. It is rather defined by the size of the object to be handled.

Application Domains. In the microscale world where a wide range of microoperations are performed, the following are distinguishing characteristics:

1. Microbody effect: As an object becomes smaller, its weight becomes lighter, and its rigidity decreases accordingly. With respect to mechanical properties, as the mass becomes smaller the characteristic frequency increases (microstructural effect). It is also more likely that, with an excess force, the object is damaged or pushed out of sight. Effects due to crystallization of material or oxidized films cannot be disregarded, and the assumption that the surface condition is uniform can no longer be taken for granted (microsurface effect). Also, a small object cannot be seen with the naked eye, and the behavior of such an object in many cases is far from our daily intuition (micro–macro gap).
2. Microfield effect: As the size of an object becomes extremely small, the scale effect prevails. In the microscale world, surface forces, such as electrostatic force, intermolecular forces, surface tension, etc., in proportion to the second power of the size become more dominant than the volume force, such as gravity, the force of inertia, etc., in proportion to third power of the size. Therefore, the handling method using gravity is no longer useful (microbody dynamic effect). In addition, the reaction of the object to the environment is sensitive. For example, many properties related to heat transfer are faster in inverse proportion to the third power of the dimensional ratio as the volume becomes small, and the thermal capacity similarly becomes smaller (micro phenomena effect).

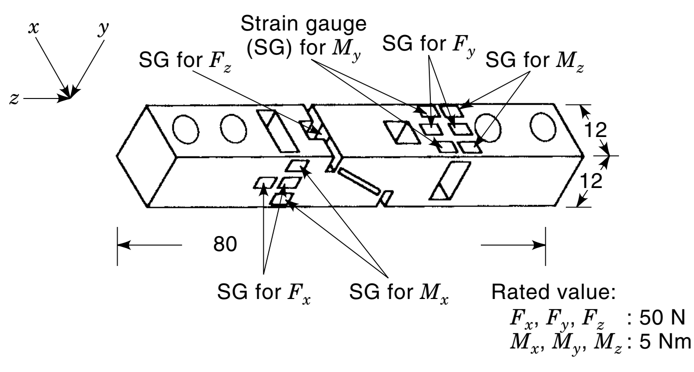


Figure 22. Structure of a bar-shaped, six-axis force sensor.

Components To Implement Microscale Operations. To produce microscale operations, the following components must be realized:

1. Microscale operating system: To implement microscale operations that go beyond human hand operations, a special device which handles the microscale object is necessary. This system provides a tool for experiencing what is going on in the microscale world. For this purpose, it is suggested that the system retain a certain degree of universality, so that it can be utilized in different applications. Such universality is typically fulfilled by a manipulator which has several degrees of freedom, including rotational motion with sufficient range of motion. In other words, first, the desired functions for handling the microscale object should be made clear. Secondly, methodologies to substantiate individual functions should be considered, and thirdly, a total system design should be conceived of which satisfies the design constraints imposed by its environment.
2. Microbody dynamics: When handling a micro object, the adsorptive force imposed on the microbody raises problems. It is impossible to fabricate tools and handling

methods by trial and error which are suitable for a particular object in a particular environment. First of all, analyses of dynamic systems (microbody dynamics) involved in tools and handling techniques are needed, although there are many cases where different kinds of forces become dominant. In most cases, however, electrostatic force, intermolecular force, and surface tension are of primary concern. To know the magnitude of these adsorptive forces during an operation, it is important, to examine them theoretically and also to take actual measurements.

3. Micro-object handling technique: When handling a microobject in which adsorptive force is substantial, control of the force is necessary. One way to get around this problem is to devise a special effector for the manipulator that generates or eliminates the absorptive force at one's instance. However, this type of control can be used only in limited cases, and in many cases such control is difficult to implement. Hence handling the object becomes insecure. To make the microhandling task more reliable, it is necessary to handle the object even in the presence of these adsorptive forces. Handling difficulties similar to the current problem are observed in everyday life when handling sticky objects, and they may shed light on micro-object handling. An appropriate account of the magnitude of absorptive forces and knowledge of microparticle dynamics are mandatory for developing successful micro-operations.

Desired Functions of a Micromanipulator. A micromanipulator that implements operations in the world of such special characteristics, must have the following functions:

1. Monitoring function: Observation by microscopy is a powerful means of measuring the fine movement of an object. To obtain visual sensory information to the fullest extent, multidirectional observability and an ability to change the direction of view, if possible, are required.
2. Visible field operation: To obtain task information from the monitoring system at any time, it is essential that the task always be executed within the visible field of the microscope.
3. Position and orientation change of the object: From the standpoint of task execution, it is highly convenient if the position and posture can be changed independently.
4. Object gripping function: The gripping and releasing function is necessary, taking into account the dominant physical principles of the microobject.
5. Reactive force monitoring function: It is necessary that microforce sensing ability be installed to prevent the object or the probe from being deformed, damaged, or lost.
6. Inconsistency rectification function: Inconsistency caused by misjudgment due to a human operator's incorrect intuition, especially in terms of the physical size of the object, must be rectified.

Basic Components of a Micromanipulation System. A microscale manipulation system is composed of a monitoring system, a manipulator, and a workbench. This subsection describes how to build these essential components.

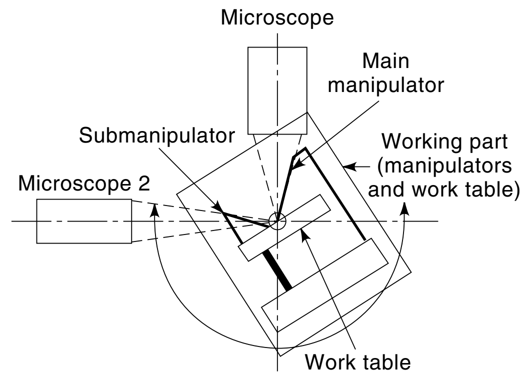


Figure 23. Concentrated visual field configuration.

1. Vision system: There is no doubt that visual information is vital in handling tasks. It is also important to achieve a system configuration so that the overall system is built around the field of view or a specific point within the view (Fig. 23). A multidirectional viewing system is composed of more than one microscope each of which monitors the same work space from different directions. These fields of view should contain the work space provided by the manipulation system. To achieve a variable monitoring direction without affecting task execution, a rotational degree of freedom should be given which rotates about the center of the field of view.
2. Manipulation system: To implement the task functions within the visual field and to attain a position and attitude control relative to an object, it is essential that all of the manipulator motions take place with respect to a specific point inside the visual field. This is typically a certain point on the object (Fig. 24). This means that all of the rotational axes intersect at the tip of the tool and the degrees of freedom are constructed sequentially in the order of the tool, the rotational degree of freedom, and the translational degree of rotation. The use of translational motions provided at the bottom of the ma-

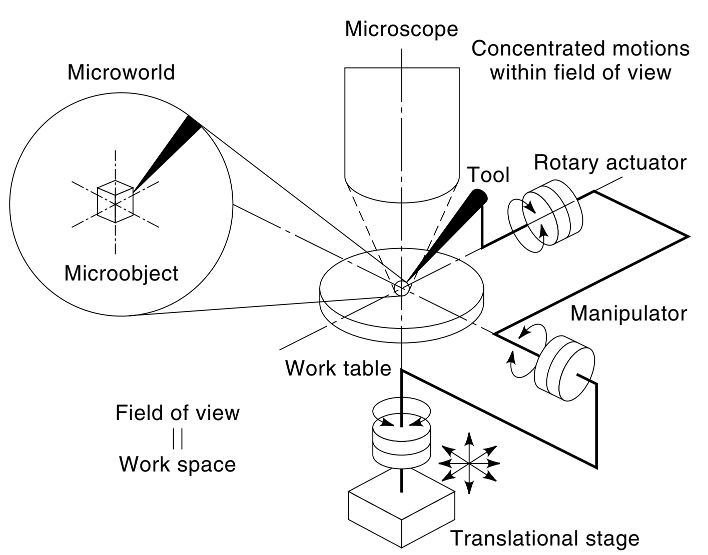


Figure 24. Concentrated configuration of motion for manipulator.

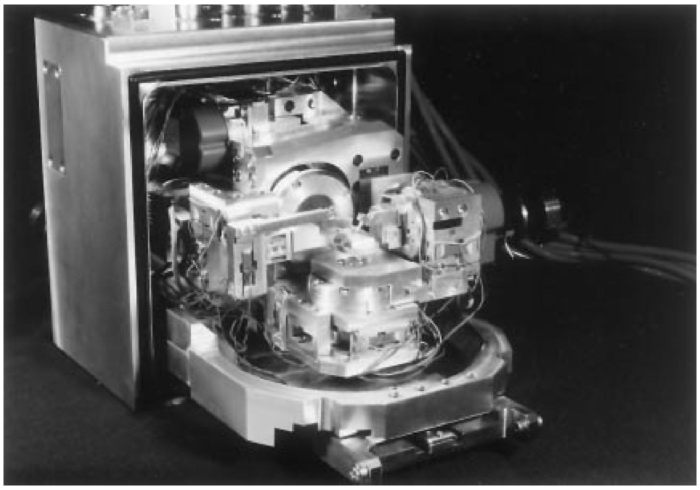


Figure 25. Photo of a microobject-handling system II.

nipulation system enables bringing the tip of the tool into the field of view of a microscope.

3. Components of the workbench: The workbench is responsible for the position and attitude control to compensate for discrepancies in position and orientation which supplement the motion of the manipulator. To achieve compensation, it is necessary to have a sufficient range of motion while assuring containment of the object within the field of view with position accuracy and without damaging the object or the tool.

Mechanism of a Micromanipulator. Following is an example of a microoperating system (Fig. 25) which consists mainly of two manipulators and two eyes all of which are coordinated to realize microoperations inside an electron microscope.

- Electron microscope: An electron microscope is employed as a main microscope, and an optical microscope is used as a supplement. These two microscopes are configured

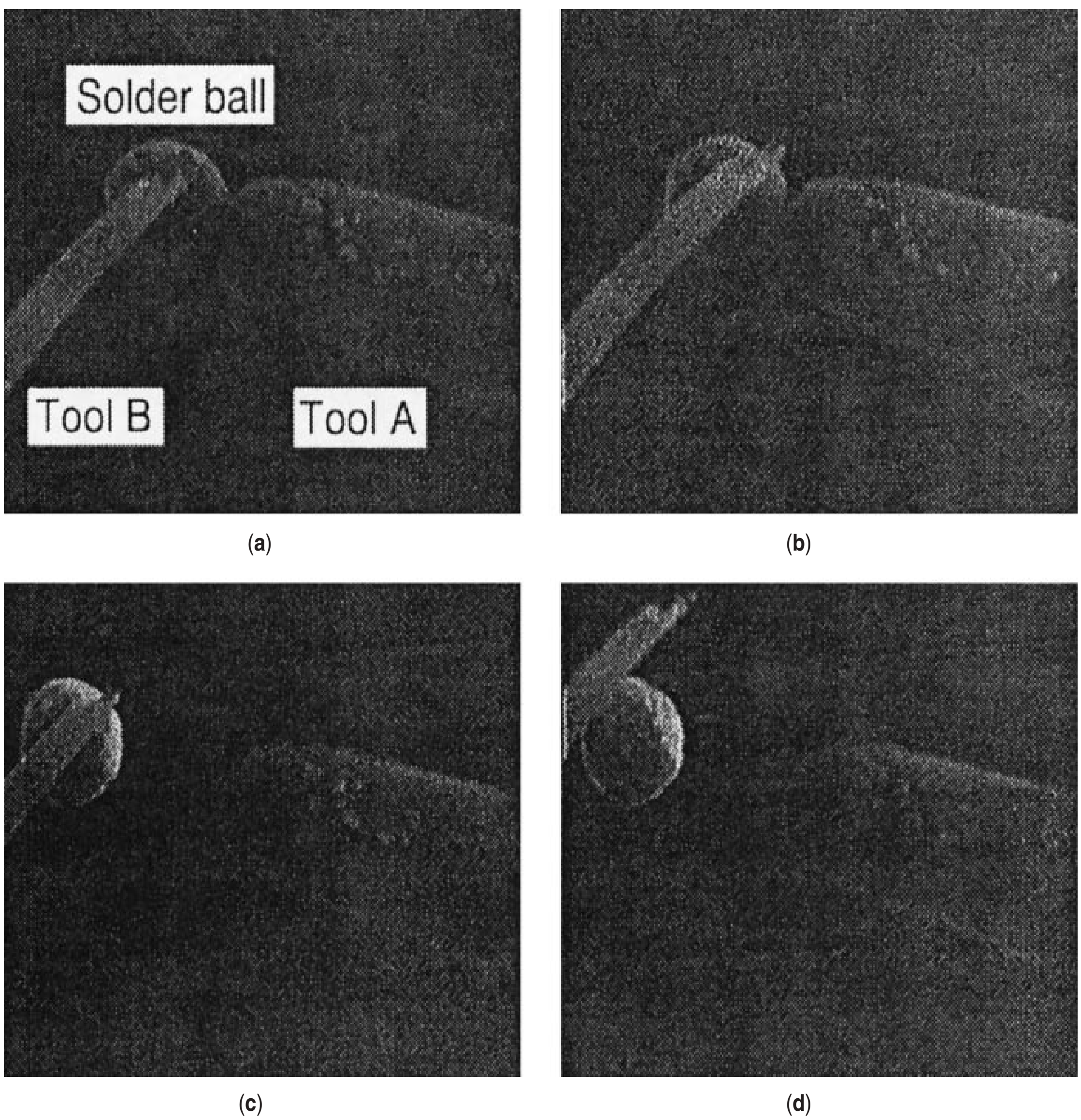


Figure 26. Placing a solder ball by holding the object still: (a) placing the object with Tool A; (b) Holding the object with Tool B; (c) Removing Tool A from the object; (d) Removing Tool B from the object.

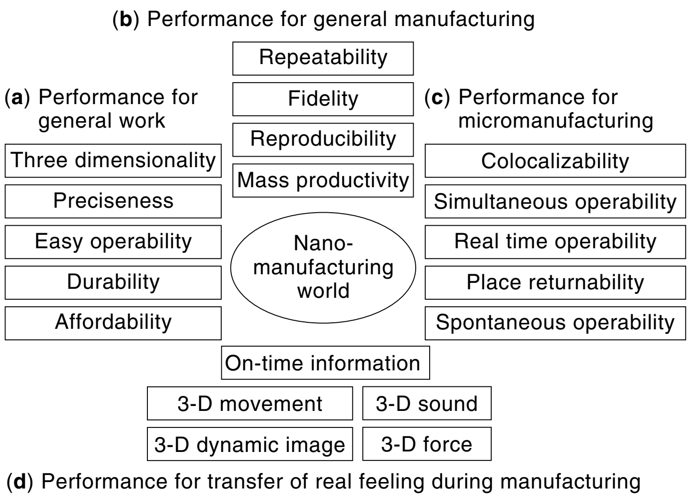


Figure 27. Groupwise functions for the Nano-Manufacturing World.

so that they provide orthogonal views and also so that their focal points coincide with each other. By the choice of such a configuration, the task space is set around the focal point of the microscopes. This system has a rotational degree of freedom about the focal point which rotates both the manipulators and the workbench relative to the microscopes and which enables varying one's gaze angle during the operation.

- Manipulators: As described earlier there are two types of manipulator, the main operating arm and an assisting operating arm. The main operating arm has two rotational degrees of freedom and three translational degrees of freedom. The axes of the rotations intersect with each other at one point, and a translation mechanism aligns the tip of the tool with that point. An ultrasonic motor (operation range: 180°; resolution: 0.1°) is used for the rotational degree of freedom, and a piezoelectric element (operation range: 17 μm; resolution: 10 nm) is utilized for the translation. Because the second arm is required to move against the main operating arm together with the workbench while gripping the object on the workbench, it is mounted on the workbench so as to maintain the position relative to the workbench. The arm has one translational degree of freedom using a piezoelectric element with a displacement-magnifying mechanism.
- Workbench: The workbench has three translational degrees of freedom in orthogonal directions. The micromotion of the workbench is realized by a piezoelectric element (operation range: 17 μm; resolution: 10 nm), and the coarse motion is taken care of by an ultrasonic motor (operation range: 10 mm; resolution: 10 μm).

Force That Works on a Microobject. A variety of adsorptive forces are observed when working on a microobject. An electrostatic force, van der Waals force, surface tension, etc. These forces may cause many problems in manipulating microobjects. In a microoperation dealing with an object several tens of micrometers in size, the effect of surface tension is small because there is no liquid-bridge formation on the surface in the normal atmospheric environment. When the surface of the object is sufficiently clean and a certain surface roughness exists, the effect of the van der Waals force also becomes small. As a consequence, electrostatic force is a dominant adsorptive force. Because an object that is not electrically grounded is always considered to be charged electrically through contact or friction, it also is necessary to take into account an electrostatic force due to charges.

Handling Techniques in Microoperation. When considering a pick-and-place operation performed by a manipulator on an object on a workbench, the adsorptive force F_t and F_w work between the effector and the object and the workbench and the object, respectively. When $F_t > F_w$, the object may be picked up by the tool, but the object picked up cannot be replaced on the workbench again. To replace the object, it is necessary to make F_t smaller than F_w. The manipulation of a microobject is produced by controlling one adsorptive force against another.

Example of Microoperation. Considering the special characteristics of surface force previously mentioned and taking advantage of the point that the adsorptive force is affected largely by contact area, a microoperating system under the electron microscope has succeeded in accomplishing a pick-and-place operation of a solder ball with two arms 20 μm in size by mechanically changing the contact area between the object and the effector (Fig. 26).

Nano-Manufacturing World and An Example of Its Operation. Fabricating a minute, three-dimensional structure involves many processes such as forming, transferring, assembling, joining, and inspection, which take place one after another. Because the object cannot be seen with the naked eye nor can be felt by hands, it is practically impossible to perform each individual operation with a separate system. To circumvent this problem, a system that performs operations from forming to assembling must be created.

The group of the functions, called for by a system that can fabricate three-dimensional microstructures, as shown in Fig. 27, submerges the operator in the world of microsubstances.

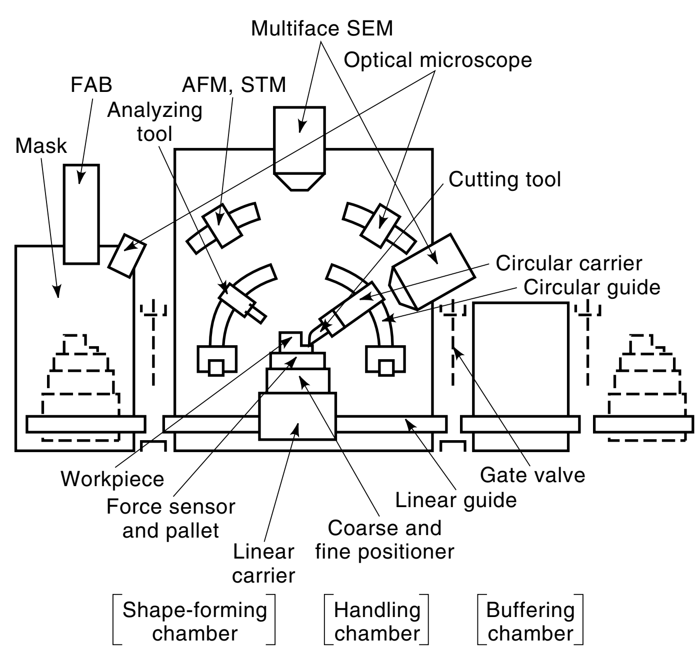


Figure 28. Construction of the Nano-Manufacturing World.

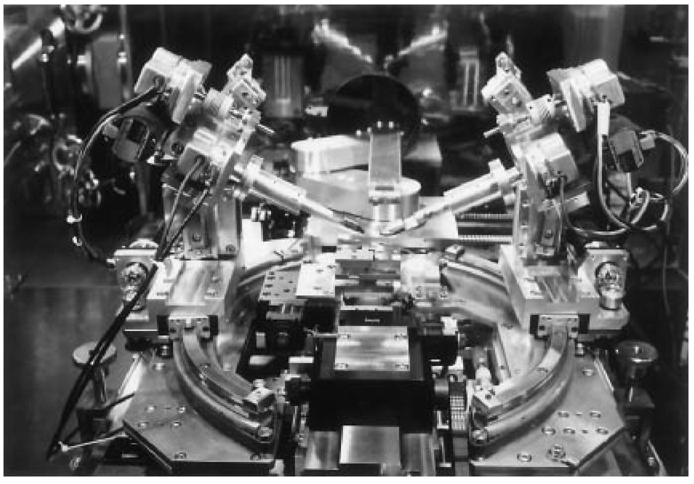


Figure 29. Front view of the manipulation system in the handling chamber.

The functions include forming using a removal process with no reactive force and assembling performed by two manipulators while observing from two orthogonal directions. A transferring mechanism also connects more than one operating site, a working space that is also used as a workbench is assured, and a parts shelf and a monitoring facility are provided to observe these situations from the external, accurate transmission of the operator's intention.

What has truly substantiated these functions, is the so-called Nano-Manufacturing World (NMW) shown in Fig. 28. Mounted on the vibration isolation table are a shape-forming chamber, handling chamber, and buffering chamber, and under the vibration isolation table are two vacuum pumps. In the forming chamber, a removal process with no reactive force takes place by a mask and fast atomic beam (FAB) forming micro parts. Then the parts formed are transferred to the handling chamber by a handling manipulator and pallet. A variety of operations are performed at the center of the operating chamber by two manipulators on the right and left. The progress of operations is monitored by a multiple-viewing scanning electron microscope (SEM) and is displayed on two CRTs. Forces and sound generated during the operations are detected by a force sensor and a microphone and are transmitted to the operator after appropriate signal processing. Using a system like this, vivid sensations and feelings are delivered to the operator as if submerged in the micro world. Operations are carried out as if the operator were dealing with an object of normal size, not a tiny object which the operator can actually see or feel.

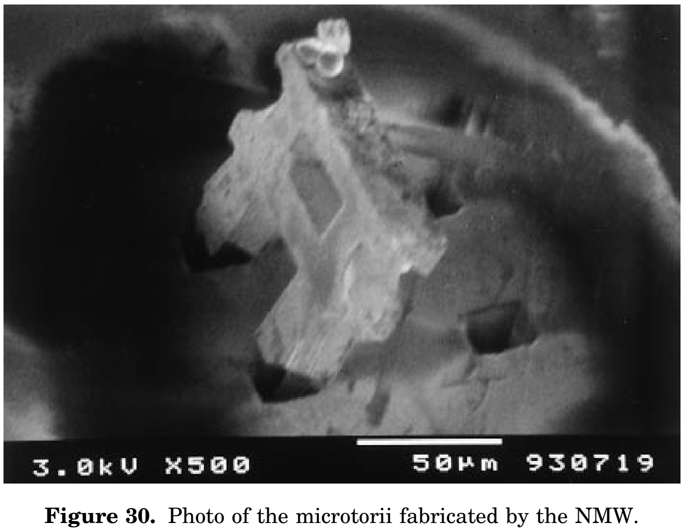


Figure 30. Photo of the microtorii fabricated by the NMW.

Figure 29 shows an example of the manipulation task in the handling chamber, and Fig. 30 is a microtorii (Japanese temple gate), an example of a micro three-dimensional structure fabricated by NMW. This microtorii is made of a crystal of GaAs and was formed by FAB. It is 80 μm high and 120 μm wide. The base is made of polyimide resin. The holes supporting the columns of the torii are 20 μm square and were fabricated using a YAG laser of the fourth harmonics. The two manipulators performed the transfer and assembly to complete the micro three-dimensional structure.

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MANUFACTURABILITY USING CAD. See CAD FOR MANUFACTURABILITY.

MANUFACTURING, COMPUTER INTEGRATED. See COMPUTER INTEGRATED MANUFACTURING.

MANUFACTURING FLEXIBILITY, SEMICONDUCTOR. See FLEXIBLE SEMICONDUCTOR MANUFACTURING.

MANUFACTURING, LASERS. See LASER BEAM MANCHINING.

MANUFACTURING OF SEMICONDUCTORS. See LITHOGRAPHY.