Chapter 1

Introduction

1.1 Historical Perspectives of Robot Design

In the early 1960's, Unimation Inc., in Danbury, Connecticut, made the first successful installation of what we call an industrial robot today. Their robot was a five-axis, hydraulically driven manipulator arm capable of carrying a several-pound payload along a predetermined path. After a careful task analysis, their robots were installed for the loading and unloading of workpieces for diecasting machines. The task involved repetitive, tedious work in a dirty, noisy and dangerous environment. The robot, capable of repeating instructed motions, met the increasing requirement for the replacement of unpleasant manual operations.

The mechanical construction of the first Unimate industrial robot departed from traditional machine design in many ways. The arm was basically a cantilevered beam structure with many degrees of freedom, most of which were revolute joints that formed a closed kinematic chain. This structure allows the robot to perform flexible motions and access a large work space compared with the space occupied by the robot itself. Also, the robot arm can operate in a crowded area as we have seen in most factory environments. Thus, the open kinematic chain meets the high mobility and flexibility requirements in the kinematic structure design. However, this kinematic structure created a number of difficult machine design problems. The positioning accuracy at the endpoint of the long cantilevered arm is considerably low; and the mechanical stiffness of the arm construction is inherently poor as well. Also, a small amount of error at each revolute joint is magnified at the arm's endpoint as the arm length gets longer. As a result, the required accuracy for the actuator driving the revolute joint must be significantly high for the articulated arm. The hydraulic actuators used for the first Unimate robot were a reasonable choice because of the high performance required for the drive system. Hydraulic drives are generally high precision, high power actuators with particularly high torque-to-weight ratio. In consequence, hydraulic robots are capable of accurate motions under severe load conditions.

As applications of industrial robots expanded, different types of robots were developed to meet a variety of task requirements. For light-duty applications, electrically-powered robots became the most prominent robot design. In arc welding, for example, electrical robots are most widely used. Compared with hydraulic drives, electro-mechanical drives are, generally, inexpensive and clean, as well as easy to maintain. Thus, electrical robots continue to replace hydraulic robots in many applications.

Electrical motors generally produce their maximum power at high speed. In other words, the electrical motors exert rather small torques while rotating at high speeds. In consequence, appropriate gearing is necessary for the electrical motors in order for these systems to drive such loads. Robot arms are usually moved at low speeds, less than one revolution per second, while required maximum torques range from a few newton-meters to several hundred newton-meters. A large gear reduction on the order of 1:100 is typically required for standard servo motors.

Design of electro-mechanical drives is complicated by the need for gearing and reducers. The reducer must provide a high gear reduction while maintaining high precision. Particularly important is that the reducer should not introduce backlash or lost motion, which will directly degrade positioning accuracy. Even a small amount of backlash at a proximal joint leads to a significantly large error at the arm tip. Hence, backlash must be completely eliminated at each joint.

Friction is another problem in the design of gearing. As described later, anti-backlash gears and other types of reducers with low backlash are characterized by considerably large friction. In many cases the motor power dissipated at the gearing amounts to over 30% of the total power because of the large friction. The large friction also leads to poor control accuracy, which is a more serious problem for high precision applications. Friction is an unpredictable characteristic, and is difficult to identify, hence difficult to compensate for.

Gearing mechanisms are often major sources of mechanical deflections or compliances. Poor mechanical stiffness not only causes static arm deflections but also limits dynamic responses. The loop gain of the servo system cannot be increased if the higher order delay resulting from the low stiffness makes the system unstable. This severely limits the bandwidth and accuracy of the drive system. Poor stiffness at the gearing may also cause undesirable vibrations.

This vibration problem is a critical issue particularly for high speed manipulation . After arriving at a specified point, the robot cannot proceed to the following step of motion, until the residual vibration caused by the gearing compliance ceases. Thus, the reduced mechanical stiffness is a crucial problem when the tact time of operations is short.

Traditionally, speed and accuracy are main issues in the design of machines. Robots are, however, somewhat different in that the speed and accuracy are not necessarily the primary goal of design. Essential robot characteristics are described by such words as flexibility, dexterity, intelligence, etc. Consequently, much research effort has addressed issues regarding how robots can be more flexible, dexterous and intelligent.

In advanced manipulation tasks, such as assembly of mechanical parts, robots perform the task through mechanical interactions with the environment. The robot is required to accommodate contact forces as well as to control the location of its end effector. Force control and compliance control are then necessary for those tasks which require control of mechanical interactions. Control schemes such as these, have been implemented on traditional robots that were primarily designed as positioning devices. The drive systems of these devices are basically position-controlled, and are not necessarily appropriate for force control . Reducers in electro-mechanical drives create significantly large friction , which provides disturbance torques in the force control system and degrades the control performance. It is also difficult for a hydraulic robot to control delicate interaction forces between the arm tip and the environment. Thus, we need an appropriate hardware tool for delicate force control and advanced manipulation.

1.2 The Direct-Drive Approach

Direct-drive is, basically, an electrical drive in which no gear reducer is used. The rotor of an electrical motor is directly coupled to the load, hence the mechanical gearing is completely eliminated. The direct-drive robot is defined to be a mechanical arm where all or part of the active arm joints are actuated with the direct drive.

Figure 1-1 shows the basic construction of a direct-drive joint from a direct-drive robot. The direct-drive joint consists of a pair of arm links, the motor, and the bearings. The motor is comprised of the stator and the rotor.

The stator is housed in the case connected to one of the arm links, usually a proximal link, and the rotor is directly coupled to the joint shaft, which is connected to the other arm link, usually a distal link. Thus the distal arm link is rotated directly by the torque exerted between the rotor and the stator, hence direct drive.

The problems that the mechanical gearing unavoidably possesses can be solved completely in the direct drive method. Backlash is completely removed and friction is reduced significantly. It may exist only at the bearings supporting the joint shaft. The mechanical construction can be much stiffer than drive mechanisms with gearing, wear of gears is no longer troublesome, and the simple construction is more reliable and is easy to maintain.

These features may result in excellent control performance. The accuracy of positioning can be improved remarkably. Since the simple mechanical construction possesses less uncertainties, eg. low friction and no backlash, the repeatability of positioning can be an order of magnitude better than that of the geared drives. The simplified mechanism will also allow us to identify the system dynamics with little difficulty. The behavior of the drive system can be modeled accurately, and thus the dynamic response is more predictable. These desirable static and dynamic characteristics make it easy and effective to apply advanced control schemes including force control and compliant motion control. Thus the direct-drive robot can be a desirable test bed for advanced manipulation studies.

1.3 The State of the Art of Direct-Drive Robots

The basic concept of a direct-drive robot was first established by H. Asada in 1980. He and his colleague T. Kanade developed the first prototype in 1981 at the Robotics Institute, Carnegie-Mellon University. Photo 1-1 shows their robot, CMU D-D Arm Model I, a six degree-of-freedom manipulator arm consisting of all direct-drive revolute joints. The first joint, the most proximal joint at the ceiling, causes a rotation about the vertical axis, while the second joint rotates the upper arm about a horizontal axis. The third joint rotates the forearm about the center line of the upper arm. The motor driving the third joint is fixed to the upper arm and is located on the other side of the elbow part, so that the motor acts as a counterweight of the elbow part. The gravity load of the second motor is then reduced with this mass balancing procedure. The

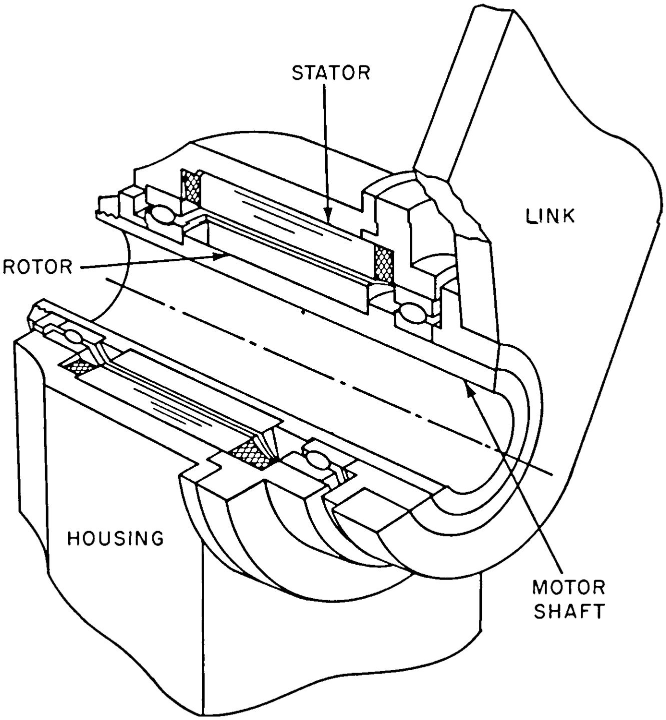


Figure 1-1: Basic construction of a direct-drive joint

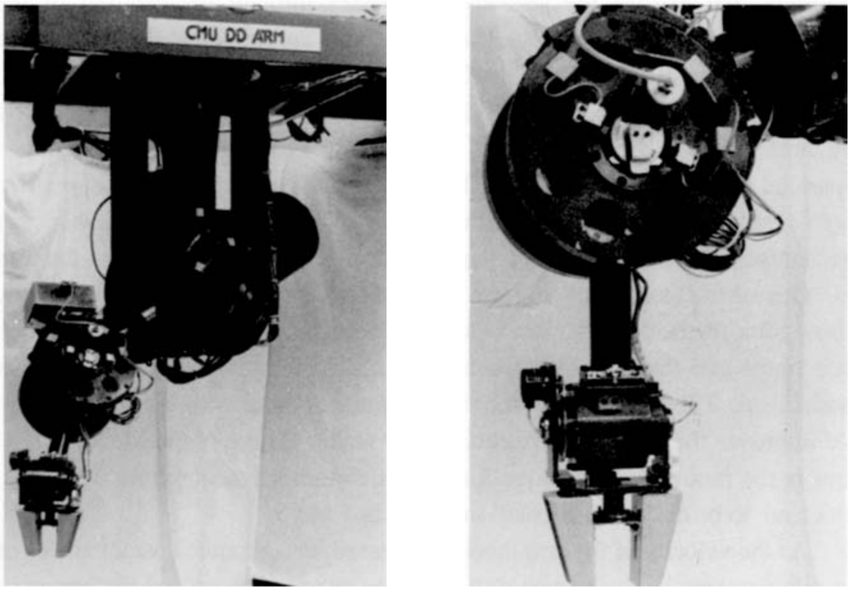
fourth joint is the elbow, causing the bending motion of the forearm, while the fifth joint rotates the forearm about its center line. The motor of the fifth joint is located within the elbow part, so that the load of the fourth motor can be reduced. The last joint is at the wrist part, bending the arm tip about the axis perpendicular to the forearm.

The motors used for the first three joints are DC torque motors using ALNICO magnets at the stators. The maximum torque of the largest motor, that is, the first motor, is over 150 Nm, while the diameter of the stator is 60 cm. The motors of the last three joints are also DC torque motors, but the permanent magnets used are Samarium-Cobalt magnets, which are more than three times stronger than the ALNICO magnet in terms of maximum magnetic energy product .

The first prototype development at the CMU Robotics Institute demonstrated the potential advantages and feasibility of the direct drive approach. The prototype design, however, revealed that the robot of this new type needs more powerful motors with more compact sizes. The motors used for the CMU Arm are not sufficient to drive the large loads, while the size of each motor is so large that the arm construction becomes too bulky and heavy.

At the Massachusetts Institute of Technology, improved direct-drive robots were developed by H. Asada and K. Youcef-Toumi. The motors used for the M.I.T. Arms are brushless DC torque motors with Samarium-Cobalt magnets, which can exert 3 to 10 times larger torque compared with the CMU Arm. For example, the largest motor of one of the M.I.T. arms can produce 660 Nm of output torque, while its stator diameter is only 35cm. In comparison with the largest motor of the CMU Arm, the peak torque is therefore 3 times larger, while the diameter reduces to a half of the previous motor.

Photo 1-2, shows the M.I.T. D-D Arm Model I , a three degree-of-freedom, serial link manipulator arm. The arm was built during the period 1982 to 1983, and is currently installed at M.I.T.'s Artificial Intelligence Laboratory. The robot has a unique kinematic structure, which allows it to eliminate gravity loads at individual motors. The first joint rotates the whole upper body about the vertical axis, hence no gravity load acts upon the first motor. The second joint rotates the forearm about the center line of the upper arm, similar to the third joint of the CMU Arm , but the motion of the upper arm is constrained within a horizontal plane. The third joint is located at the elbow, and causes the bending motion of the forearm. Since the mass of the forearm is balanced with its counterweight, the third motor does not experience any gravity load .



degrees of freedom	6
material	Aluminum
special features	Serial drive

Photo 1-1: The Carnegie-Mellon University Direct-Drive Arm model I

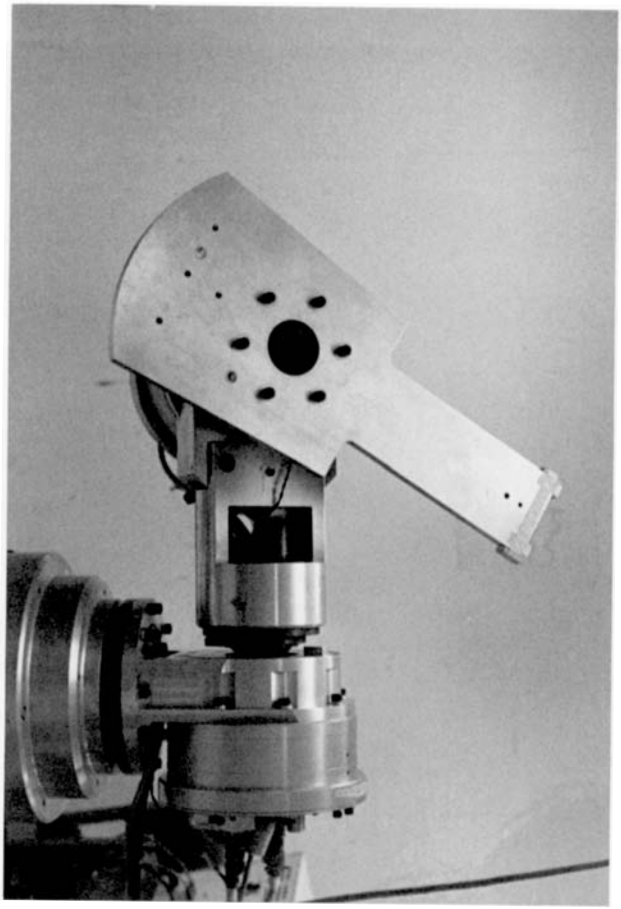
Similarly, the axis of the second joint passes through the centroid of the forearm, hence no gravity load acts on the second motor. Thus all three motors have no gravity load for all arm configurations.

Photo 1-3 shows the M.I.T. D-D Arm Model II, which was developed by the same group at M.I.T. from 1983 through 1984. For this arm, they employed a parallel drive mechanism with a closed-loop kinematic chain. The upper two motors, located on the base frame, drive the two input links of the parallelogram mechanism, which causes a two degree-of-freedom vertical motion at the arm tip. One of the features of this arm construction is that the heavy motor at the elbow joint of the previous model was replaced by the motor mounted on the base frame and that the drive torque is transmitted through the parallelogram mechanism. This remote drive mechanism reduces the arm weight significantly and improves the dynamic performances. Another feature of the Model II D-D Arm is the innovative technique for dynamic mass balancing and decoupling, which are to be discussed in detail in Chapters 4 and 5.

As the velocity of the arm motion increased, the dynamic characteristics of the arm construction have more critical influence upon the control performance. Photo 1-4 shows the M.I.T. D-D Arm Model III with a linkage made out of graphite composite material. Since the material is lightweight and strong, the arm's stiffness as well as the inertia are improved significantly. The natural frequency of the arm construction was then increased to about 70 Hz, whereas the Model II Arm, which was made of aluminum, had a natural frequency of only 14 Hz. With this lightweight, high stiffness arm structure, the M.I.T. D-D Arm Model III has achieved an extremely fast motion: The maximum tip speed is 12 m/s and the maximum acceleration is over 5 G.

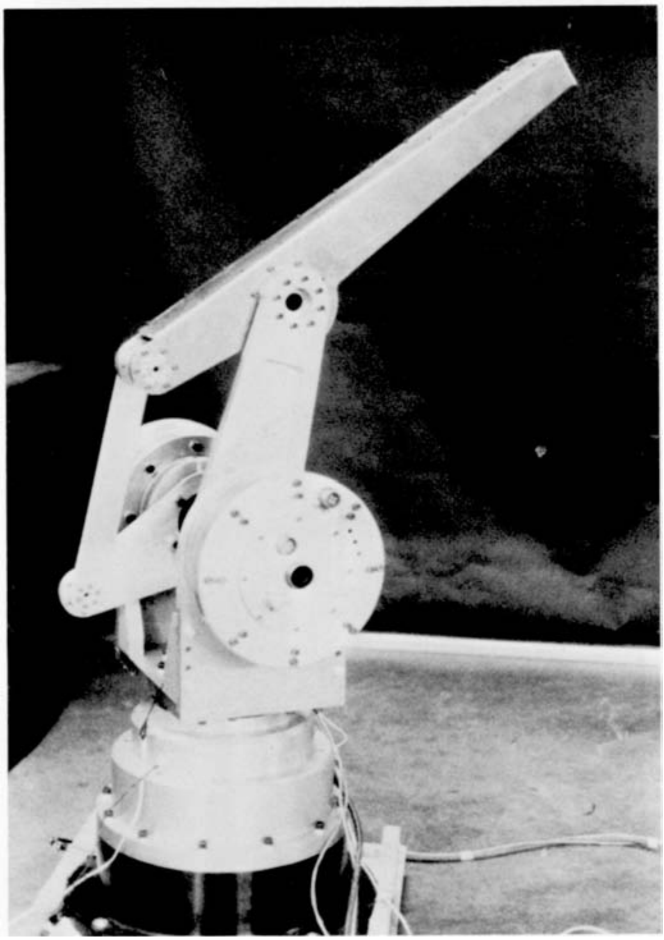
Photo 1-5 shows another type of direct-drive arm developed at M.I.T., the M.I.T. D-D Arm model IV. The two motors aligned on a vertical axis drive the horizontal parallelogram mechanism. Since the link motion is constrained within a horizontal plane, no gravity load acts upon the two motors. Robots with this type of kinematic construction are often referred to as SCARA robots , which are widely used for assembly operations, particularly for planar assembly tasks.

The simple construction of the SCARA robot is appropriate for direct-drive robots: small number of degrees of freedom as well as the no- gravity-load construction make it easier to build practical robots. In fact, the first commercialized direct-drive robot employed the same kinematic construction as the SCARA robot. Photo 1-6 shows the AdeptOne direct-drive robot developed



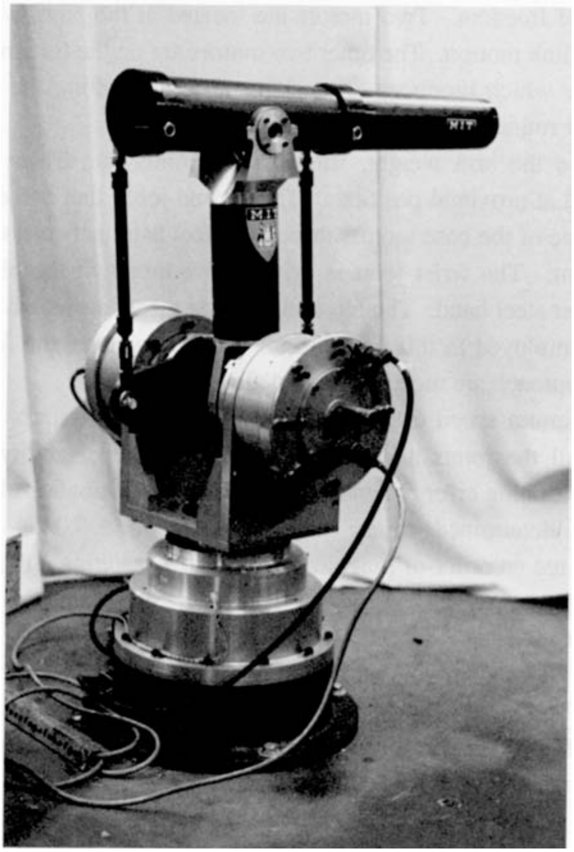
degrees of freedom	3
material	Aluminum
special features	gravity balanced, serial drive

Photo 1-2: The M.I.T. Direct-Drive Arm Model I



degrees of freedom	**3**
material	**Aluminum**
special features	**decoupled dynamics, parallel drive with a five-bar-link mechanism**

Photo 1-3: The M.I.T. Direct-Drive robot Model II



degrees of freedom	**3**
material	**Graphite Composite**
special features	**decoupled dynamics, parallel drive with a six-bar-link mechanism**
application	**laser cutting**

Photo 1-4: The M.I.T. Direct-Drive robot Model III

by ADEPT Technology Inc., at Sunnyvale, California, in 1983. The arm has four degrees of freedom. Two motors are located at the base, which produce the horizontal link motion. The other two motors are on the forearm: one drives the lead screw which produces a translational motion along the vertical axis, while the other rotates the gripper about the vertical axis.

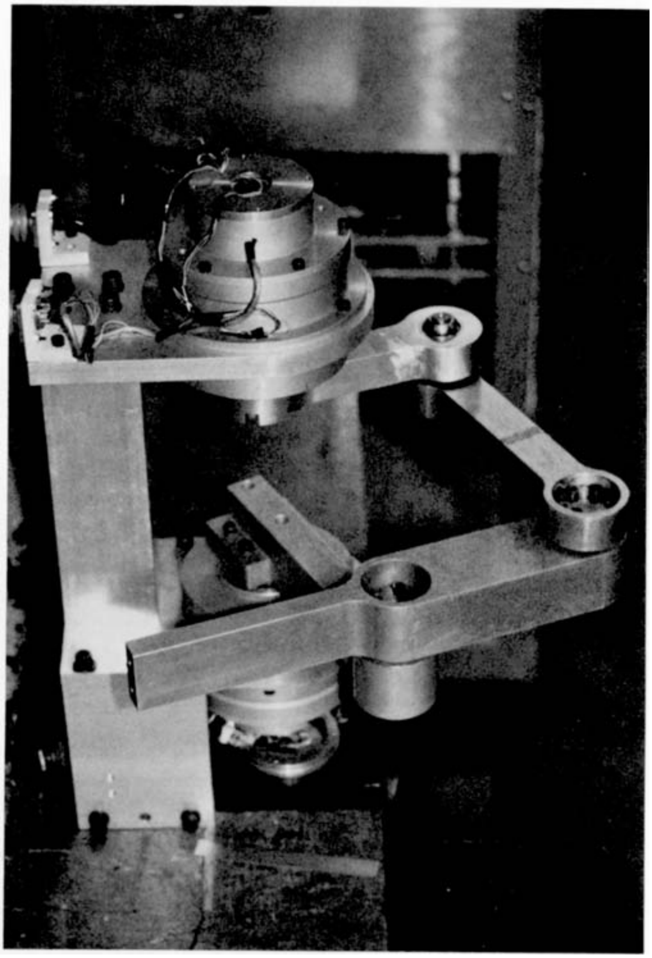
To reduce the arm weight, some of the joints are driven remotely by motors located at proximal positions. The second joint, that is the elbow joint, is driven by one of the base motors through a steel band between the motor and the elbow joint. The wrist joint is driven by a motor at the elbow position through another steel band. Though transmission mechanisms are used, no gear reducers are employed in this arm design. In consequence, the features of the direct-drive approach are mostly maintained.

The maximum speed of the arm is 9 m/s, which is defined to be the tip speed when all the joints are at slew speed. The repeatability, that is, the maximum positioning error when reaching the same destination along the same trajectory, is determined to be ± 0.001 inch or ± 0.0254 mm. Both specifications are an order-of-magnitude better than traditional robots with gear reducers.

The motors used for the AdeptOne direct-drive robot are specially designed high torque motors produced by Motornetics Inc. in Santa Rosa, California. As described in detail in the following chapter, the motor is a 3-phase variable reluctance motor having many teeth at the rotor. The motor produces a large torque with small power consumption, when rotating at low speeds.

Photo 1-7 shows another direct-drive robot commercialized by the Matsushita Electric Industrial Co., Ltd., Osaka, Japan. The robot has the same kinematic construction as that of the M.I.T. Arm Model IV, namely the horizontal parallelogram mechanism. The arm length is about 60 cm, a little smaller than the AdeptOne robot. The motors used for the Matsushita robot are brushless torque motors with Samarium-Cobalt magnets . One of the features of the Matsushita robot is that the motor, when incorporated with a high performance drive amplifier , has an excellent linearity, while producing a large torque with a small torque ripple. This allows us to improve the control accuracy not only positioning control but also for the torque control. One can also change the endpoint compliance in a wide range; it can be extremely soft or hard by simply changing the gains of the drive system.

Another feature of the Matsushita robot is its high accuracy. Precision



degrees of freedom	**2**
material	**Aluminum**
special features	**decoupled and invariant dynamics, parallel drive with a five-bar-link mechanism**
application	**assembly**

Photo 1-5: The M.I.T. Direct-Drive robot Model IV

Photo 1-6: AdeptOne direct-drive robot
(Courtesy of Adept Technology, Inc.)

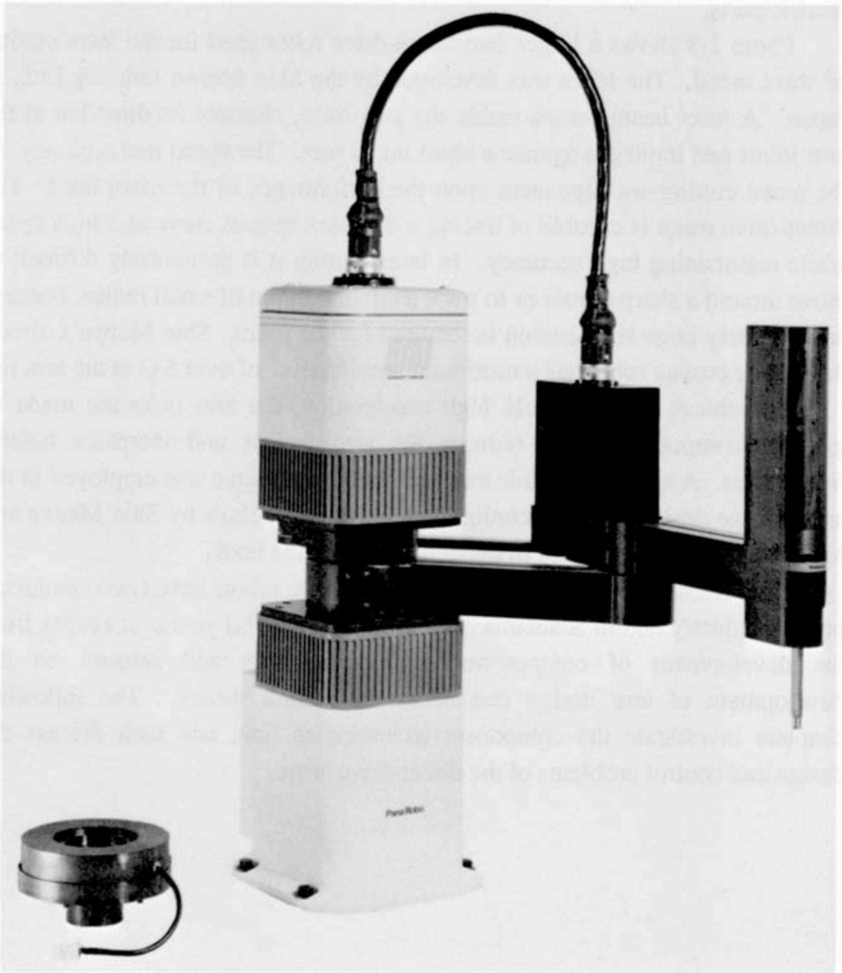


Photo 1-7: The Matsushita Direct-Drive Robot
for high speed assembly, Pana Robo HDD-1.
(Courtesy of Matsushita Industrial Co., Ltd.)

position sensors were specially developed for the direct-drive robots. The sensor is a laser interferometer type encoder, having a high resolution . With this encoder and the motor drive system, the repeatability of the Matsushita robot is less than ± 0.010 mm or ± 0.0004 inch. This will meet increasing needs for high accuracy operations, particulary in precision assemblies of electric parts.

Photo 1-8 shows a larger size direct-drive robot used for the laser cutting of sheet metal. The robot was developed by the Shin Meiwa Industry Ltd., in Japan. A laser beam passes inside the arm links, changes its direction at the arm joints and impinges against a sheet metal part. The speed and accuracy of the metal cutting are dependent upon the performance of the robot used. The direct-drive robot is capable of tracing a complex spacial curve at a high speed while maintaining high accuracy. In laser cutting it is particularly difficult to move around a sharp corner or to trace a circular curve of small radius, because an extremely large acceleration is required for the robot. Shin Meiwa's direct-drive laser cutting robot has a maximum acceleration of over 5 G at the arm tip.

To achieve the extremely high acceleration, the arm links are made of graphite composite, which reduces the arm weight and increases natural frequencies. A special dynamic mass balancing technique was employed in the arm linkage design. These techniques used for both robots by Shin Meiwa and Matsushita will be discussed in detail in Part II of the book.

Thus research and development of direct-drive robots have been conducted both in industry and in academia during the past several years. It ranges from the development of components, such as motors and sensors, to the development of arm design and necessary control theory. The following chapters investigate the component technologies first, and then discuss the design and control problems of the direct-drive arms.

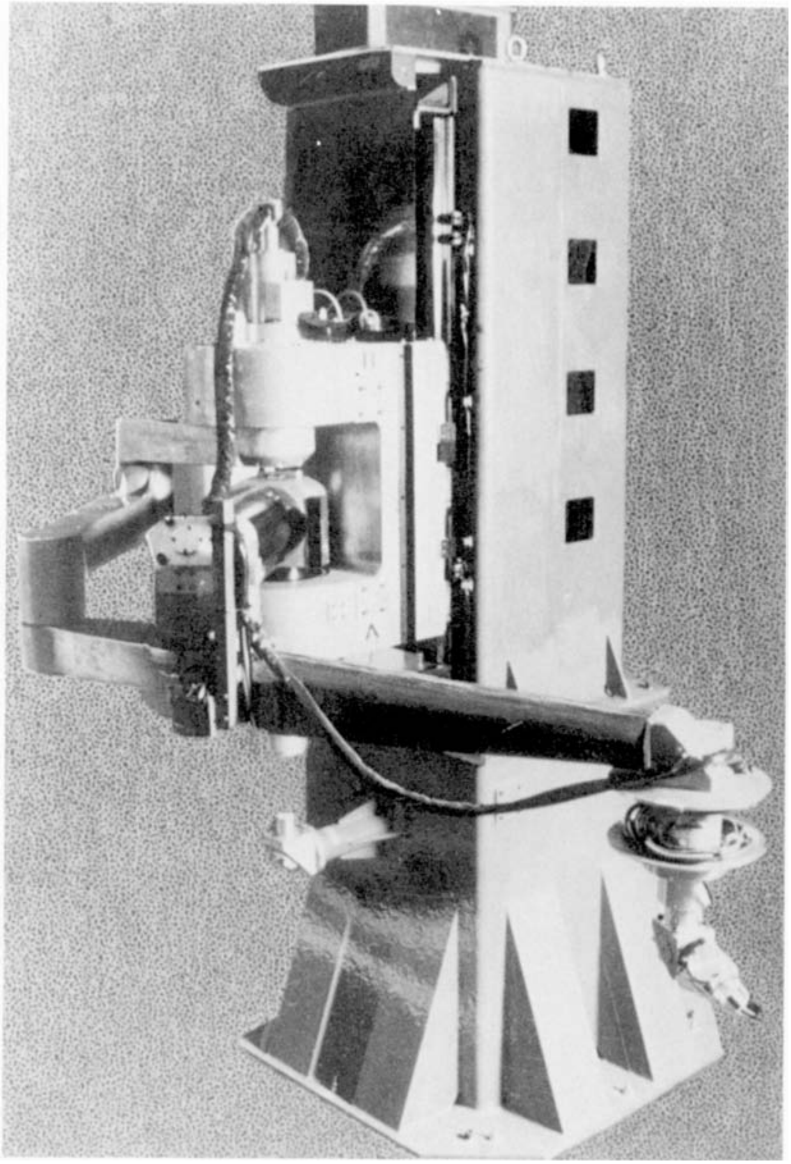


Photo 1-8: The Shin Meiwa Direct-Drive robot for high speed laser cutting applications.
(Courtesy of Shin Meiwa Industry Co., Ltd.)