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Review -

3.5.1 Definitions of Mechanical Terms

Several terms are used here which require definition to ensure that we are all attaching the same meaning to them. Many other terms are defined in the Glossary (Appendix C).

1. Accuracy. The absolute measurement of a quantity in relation to a reference base. Positioning accuracy is defined as the difference between the position desired and the position actually achieved. In most industrial robot work, it is given in inches or millimeters. Both positive and negative rs are specified.
2. Cycle Time. the time, in seconds, for a robot arm to carry out a specific operation or task. Typical cycle time specifications are full extension of an arm, rotation from extreme left to extreme right, or the time required to carry out a complete task such as picking up an object from a pallet and placing it in a machine tool.
3. Joint. A mechanism that allows relative movement between parts of a robot arm. Sliding joints allow links (separate arm sections) to move in a linear relationship. These joints are also called "prismatic" because the cross section of the joint is considered to be a generalized prism. Rotary joints allow only angular motion between links. Some joints are designed to allow both rotary and linear motion, however, they can always be considered as two separate joints for analysis.
4. Link. One portion of a robot arm separated by either linear or rotational joints. It is analogous to the human lower arm, upper arm, and so on.
5. Reliability. A measure of the length of time a robot will operate without failure. Mean time between failures (MTBF), stated in hours, is commonly used to indicate the reliability of a device. Another related measure, is mean time to repair (MTTR), also stated in hours. We want MTBF to be a maximum and MTTR to be a minimum, of course.
6. Repeatability. A measure of the difference between successive movements to the same commanded position. Repeatability in many robot arms is very good. Even though the actual position is in error the robot may move to the previous position with only a small difference. Note that the factors causing inaccuracies may not have much effect on repeatability. Deflection due to gravity will cause the same error every time, but the error will be repeatable. Backlash may vary, of course, since it is affected by friction and load effects.
7. Resolution. A measure of the size of the steps between positions. It is usually stated in steps per inch or per centimeter. It has the same meaning for mechanical positioning as optical resolution does in optics, where it may be stated in lines per millimeter. Digital devices, which determine position by discrete steps, always have a finite number of possible steps. Analog devices, in theory, could have an infinite number of steps. Accuracy and resolution are not necessarily related. A device could move to a commanded position with perfect accuracy, but if the resolution was low, it might not be in the position required.
8. Speed. The time rate of change in position. It is often given as a substitute for linear velocity or angular velocity. (See item 9)

3.5.2 Design Considerations

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CRITCHLOW

9. Velocity. A measure of the speed and direction of motion. It is a vector quantity, which means that both the speed and direction must be stated. Linear velocity is measured in inches per second, or in millimeters per second; angular velocity is measured in degrees per second or radians per second. Direction of motion may be stated in any coordinate system or in terms of angular relationships.

Other mechanical terms are defined in the Glossary.

3.5.2 Design Considerations

Desirable operational characteristics for a robot must be designed in. Therefore all of the necessary characteristics must be considered as part of the overall system. Clearly, for example, we could attain very high rigidity and accuracy by making all links massive and all joints highly precise, but at the cost of higher cost and slower operation.

1. Operating Cycle

A robot is not very useful if it cannot carry out a task in a reasonable amount of time. Usually a robot must compete with an alternative—a human worker or another type of machine. It must therefore operate rapidly enough to be cost effective compared to the alternative. In practice, this means that a complete operating cycle must take place in a few seconds.

Cycle time can be decreased in several ways. Increased drive power can be used, the mass and moment of inertia of joints and links can be reduced, or the means of control can be improved to perform the operation more efficiently, with less lost motion. All of these approaches are commonly used in design.

Mechanical analysis and simulation can be used to determine the critical parameters, and those parameters can be optimized. As discussed in Chapter 4, there are several types of drive motors available, some with high inertia and some with lower inertia. Whenever possible, the motors with lower inertia and lower weight are chosen.

Commonly, the arm links of a robot are tapered so that they are strong enough to provide the desired rigidity but do not have unnecessary stiffness. One manufacturer, Graco, has built a robot arm from graphite fibers to attain maximum stiffness with minimum weight.

Control methods to optimize the operating cycle are discussed in Chapter 6. Computer control to select the optimum trajectory has been refined so that much greater operating efficiency can be attained. In addition, new mathematical methods have reduced the computation required to determine a trajectory and perform a task.

2. Accuracy and Repeatability

As discussed in Section 3.5.3, several factors affect accuracy. It is important to consider these factors during the early stages of design to ensure that an optimum design is obtained. In addition, great care must be taken in fabrication to ensure that parts are machined to the required dimensions and that the materials selected are suitable for the purpose. There is no substitute for care in design and fabrication. In addition, the individual items must be carefully inspected and tested to be certain that they meet the design specifications.

Dimensional stability in mechanical parts should be considered. Metals can bend and creep during fabrication. Although they are initially machined to the correct dimension, there are changes due to stress release that can cause errors in the finished parts. These errors can be detected and eliminated by good shop practice and careful heat treatment.

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3. Life Expectancy, Reliability, and Maintainability

Robots are expected to have a useful life of at least 40,000 working hours. Well-designed robots are expected to have an MTBF of at least 400 hours and an MTTR of no more than 8 hours (Engelberger [6]). In practice, over the last 10-year period, the Unimate® robots, for example, have demonstrated 98% up-time. That is, during the time when they are expected to be available, they have been available and ready to work 98% of the time. Up-time does not include the scheduled periods for preventive maintenance.

One means for decreasing MTTR is to modularize the design so that parts are easily replaceable and a minimum number of parts is required. Then, with a small stock of spare units, it is possible to do maintenance quickly by replacing the unit. In this way, the skill required for maintenance is reduced to the ability to replace the component. Rebuilding of components can be done at the factory by skilled personnel. Yearly maintenance costs are expected to be about 10% of the acquisition costs of a robot and associated equipment when the robot is working two shifts or 4,000 hours per year. This important subject is discussed in considerable detail in Chapter 5 of Engelberger [6].

3.5.3 Mechanical Positioning Accuracy and Repeatability Factors

Six major items affect positioning accuracy and repeatability in a robot:

REVIEW ERRORS

1. The force of gravity acting on the arm members and load of the robot causes downward deflection of the arm and the support system.
2. Acceleration forces may act in any direction. Noticeable horizontal and vertical deflections occur when heavy loads are being accelerated.
3. Drive gears and belt drives often have noticeable amounts of slack that can cause positioning errors.
4. Thermal effects can expand or contract the links of the robot arm. In large robots, this effect can be of considerable magnitude.
5. Even bearing "play" can be significant when very high positioning accuracies are desired.
6. Windup can be important when long rotary members are used in the drive system and twist under load.

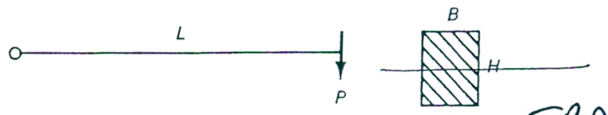
Errors due to sensor and control errors are considered in Chapters 4, 5, and 6 and will not be covered in this chapter.

The following sections provide a simplified analysis of the major factors affecting accuracy and repeatability.

1. Gravitational effects

F = Mr α

To approximate the effect of gravity on a robot arm, we consider a steel cantilever beam of length, L, width, B, and height, H, fixed at one end and with a force, P, applied at the free end due to gravitational force on the load. Deflection D of this beam due to the force of gravity is given by equation (1).



GRAVITY

$$D = \frac{PL^3}{3EI} \quad (1)$$

where E = Young's Modulus, 30.0 X 10^6 pounds per square inch for steel and $I = BH^3/12$ is the moment of inertia for a rectangular beam of width, B, and height, H taken about a horizontal line through its center. All dimensions are in inches, and the force is in pounds. (We are neglecting the weight of the beam in this simple example, which is used only to illustrate the error due to gravitational effects.)

We will use the following values in equation (1) to ascertain the magnitude of the deflection of a robot arm under a load:

P = 100 lbs.	Load on the end of the arm.
L = 60 inches	Length of the arm (5')
B = 4 inches	Width of the arm link.
H = 6 inches	Depth or vertical dimension of the arm.

Inserting these values in equation (1), we find that D = 0.0033 inch, which is an acceptable value for the deflection. Note that this is a repeatable deflection obtained whenever the same conditions apply. In this case, the inaccuracy due to deflection is 0.0033 inch, but the repeatability error may be only a few ten-thousandths of an inch if the same load is applied again. Since an arm made up of multiple links and joints has an effective horizontal length that is changing, we can expect the error due to gravitational effects to vary as well. Note that the deflection is a function of the cube of the depth of the arm. Where we had a deflection of 0.0033 inch for H = 6 inches, the deflection would increase to 0.0111 inch with H = 4 inches. This deflection error may not be acceptable.

2. Acceleration Effects

In a cylindrical coordinate system, for example, an object being carried around the vertical with an angular velocity of w is subject to a radial force (assuming a point mass)

$$F = \frac{d}{dt}\vec{p} = \frac{d}{dt}$$

$$F_r = mrw^2 \quad (2)$$

where m = W/G is the mass of the object being carried,
W = weight of the object, in lbs.,
G = the gravitational attraction, 32.2 feet per second squared,
r = the radius of the path of the object's center of mass,
w = the angular velocity of the end of the arm in radians,
F_r = is given in pounds when the radius is in feet.

Angular deflection, D_a due to angular acceleration a_a is horizontal and of magnitude:

$F = Mr\,a_a$

$$D_a = (mra_aL^3)/(3EI) \quad \text{as in Eq(1)} \quad (3)$$

where $I = (B^3H)/12$ for the horizontal moment of inertia when B is the width of the beam, H is the depth, and other terms are as previously defined. Since the radius and the length of the arm are the same, we can replace Equation (3) with $D_a = (ma_aL^4)/(3EI)$.

In normal operation this deflection is neglibile, but it becomes important in some types of high-speed operation where the end of the robot arm starts and stops quickly. The resulting whipping motion takes some time to settle to zero position error and may not be zero before the arm is moved again, thus introducing a position error.

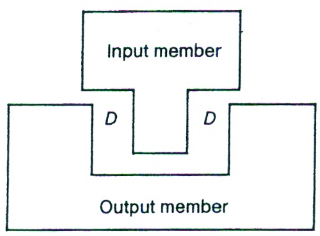
When a robot arm is designed, this effect must be taken into account because of the side force due to acceleration on the components of the arm itself.

3. Backlash Error

Backlash due to gearing or belt drives is another source of error in attempting to get high positioning accuracy and repeatability.

Gears do not mesh perfectly but have spaces between them, as shown in Figure 3.20. Note that the input member has spaces, D, between each side of the tooth and the output member. It is therefore necessary for the input member to move distance D before it can cause the output member to move. Any error at this point is multiplied by the gear ratio between the input gears and the final position of the robot arm or other member. Chains, belts, and other drives have the same kind of potential error. Some of this error can be taken out of the system by using very precise gearing or anti-backlash gearing, which is spring loaded to hold the input gear against one side of the driven gear. This solution is limited to the available strength of spring restraints.

Figure 3.20
Model of backlash.



Backlash, with good gearing, can be held to less than 0.010 inch, but it becomes a difficult problem when positioning accuracies of 0.001 inch are desired.

In addition to the positioning errors caused by backlash, it is a potential source of oscillation due to the introduction of phase errors in the servo system.

4. Thermal Effects

Several robot manufacturers quote positioning accuracy and/or repeatability specifications of 0.001 or 0.002 inch. It is important to understand the conditions under which these specifications are valid. It is easy to calculate the amount of variation in the fully extended arm as a function of temperature using the equation:

$$V = Lc(T_2 - T_1)$$

where L is the length of the arm, c is the coefficient of linear expansion per degree, T_2 is the final temperature, and T_1 is the initial temperature.

As an example, we can use the following values in this equation:

L = 60 inches
c = 6.5 X 10^{-6} per ^{O}F, for steel.
T_1 = 60^{O}F
T_2 = 80^{O}F

THERMAL

Therefore

$$V = 60 \times 6.5 \times 10^{-6} \times (80 - 60)$$
$$= 7.8 \times 10^{-3} = 0.0078 \text{ inch}$$

This is enough movement to cause a significant error. There may be some compensation due to other thermal expansions, but the net effect is large enough to be worth careful analysis.

5. Bearing Play

Bearing play is usually an insignificant source of error. Good bearings can hold tolerances of 0.0001 inch. In ordinary industrial robots, therefore, we can neglect this source of error. However, when a linkage revolves about a bearing and has a long lever arm, the possibility of bearing play should be considered.

6. Windup

Windup is the angular twisting, under load, of rotary drives or shafts. When windup is outside the servo loop, it must be kept small. Inside the servo loop, it is of less concern. The amount of windup can be calculated from

$$\Theta = \frac{32LT}{3.1416\, D^4 G}$$

where L = length of the rotating member, T = torque, in inches per pounds, D = diameter, in inches, G = shearing modulus of elasticity (psi), and Θ = amount of twist in radians.

The shearing modulus of elasticity, G, is 12.5 X 10^6 psi for steel.

3.4 End Effectors

End effectors are the pickup devices, grippers, hands, and tools mounted on the end of the robot arm. These are the devices that perform the actual task. This general class of devices is also called end-of-arm tooling (EOAT), but we will use the simpler term, end effectors. End effectors are often designed for a particular task, but can also be made as all-purpose hands to do many types of tasks.

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Robot end effectors are much better than human hands in dealing with heavy objects, corrosive substances, hot objects, or sharp and dangerous objects. They are not as good at handling complex shapes and fragile items. Also, since the current hands do not have good tactile sensing capability, they cannot do the many complex tasks that humans do by touch alone. However, new sensors, as described in Chapter 6, can provide useful tactile capability for many applications.

Examples of end effectors are given in Figures 3.17, 3.18, and 3.19. Engelberger [6] describes several other end effectors.

3.4.1 Grasping and Holding Techniques

Many different techniques are used to provide the grasping or holding function in a robot end effector. Obvious techniques are:

1. Vacuum cups
2. Electromagnets
3. Clamps or mechanical grippers
4. Scoops, ladles or cups
5. Hooks
6. Hands with three or more fingers
7. Adhesives or strips of sticky tape

3.4.2 Qualifications for End Effectors

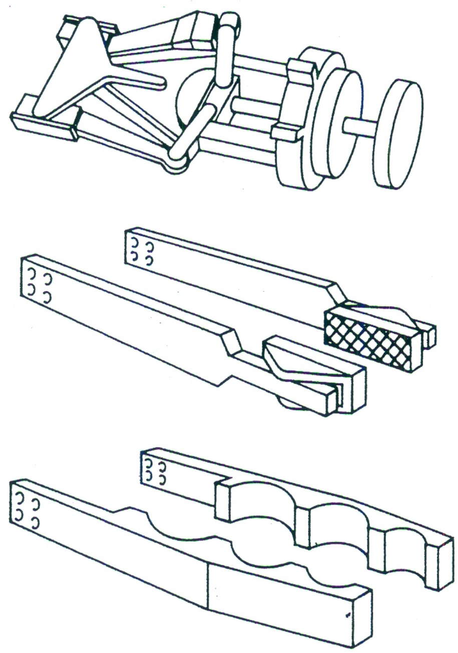
1. Grippers

Since many different tasks are performed by robots, it is not surprising that there are many different requirements for gripper end effectors. Some of these requirements are:

TOUCH + SLIP KLAFTER p 382 - 415

1. Parts or items must be grasped and held without damage.
2. Parts must be positioned firmly or rigidly while being operated on.
3. Hands or grippers must accomodate parts of differing sizes or even of varying size.
4. Self-aligning jaws are required to ensure that the load stays centered in the jaws.
5. Grippers or end effectors must not damage the part being handled.
6. Jaws or grippers must make contact at a minimum of two points to ensure that the part doesn't rotate while being positioned.

Some of these characteristics are illustrated in Figure 3.17.



(a) Standard hand. A large variety of custom-made fingers can be attached to this all-purpose hand. Air- or solenoid-operated linkages provide the necessary clamping pressure to hold the item tightly. Parts of moderate weight can be handled reliably by this hand.

(b) Self-aligning fingers. Pivoted pads for fingers tilt to align with the part. This arrangement works well for flat-sided parts or those that have only a small angular difference between the sides. They can be mounted on the standard hand with bolts or screws.

(c) Multiple-cavity fingers. These fingers can handle three sizes of parts. By positioning the robot hand, the cavity which best fits the parts can be selected.

Figure 3.17 Examples of mechanical grippers.

Source: Robotics in Practice by J.F. Engelberger, page 45.

The clamping force required to hold parts must be adjusted to ensure that the part does not slip loose and yet is not damaged by the tight grip. Parts may be supported because the clamp has closed around an edge or protuberance on the part, or the part may be held by friction. Usually the part is held by the friction force, which is composed of pressure against the part due to the clamping force (the "normal" force of engineering dynamics) and a coefficient of friction due to the roughness or resilience of the contacting surfaces.

2. Friction Holding

If a part is to be held reliably, the friction force must be greater than the total of all the forces being applied—gravitational force, centrifugal force, and so on. Friction force is defined as:

$$F_f = \mu F_c$$

where F_c is the clamping force and μ is the coefficient of friction. In a typical case, to hold a load of 50 pounds, we would need a clamping force of 100 and a coefficient of friction of $\mu = 0.5$ as a minimum. Actually, it would be desirable to have a factor of safety of at least two, so a clamping force of 200 pounds would be required.

Most robots use only one arm to handle objects, while humans use two arms when necessary. When large objects are to be handled, the human may pick up the object with one hand at each end. A robot will use one end effector that has been designed to handle a specific class of objects. The cost of end effectors is usually a small part of the total cost of the robotic system, so that specialized end effectors make good sense.

Usually the robot arm has a tool holder at its end to simplify the attachment of end effectors. This holder could be a bayonet pin mount or a plate with mounting holes. Bayonet pin mounts have a long, pointed shaft that fits into a support sleeve and a shorter pin that fits into another alignment hole to prevent the end effector from rotating. Both pins are secured in place by clamp rings or other means to prevent the end effector from being released accidentally. These mounts are similar to those used in quick-change machine tools. Mounts of this type allow automatic changing of end effectors. Solenoids can be used to release the clamping ring or pin used to hold the end effector or tool in place.

3. Vacuum Handling

BMW WINDSHIELD

Large sheets of metal or plastic can be picked up by using multiple vacuum cups on the end effector. Each cup is attached to the vacuum pump, so that the pressure differential inside and outside the cup is maintained. It is easy to maintain a differential of 10 pounds per square inch with a small vacuum pump.

Calculation of the vacuum cup area required for a desired grasping force is performed simply. As an illustration, assume that a horizontal metal plate weighing 100 pounds is to be picked up. Then the vacuum cup area required on the end effector is calculated from the formula

$$A = \frac{W}{(P_o - P_i)N}$$

where N = number of vacuum cups on the end effector.
W = weight of the plate
P_o = outside pressure (standard atmospheric pressure), and
P_i = inside pressure.

HOLDING

When $N = 4$, $W = 100$ pounds, $P_o = 14.7$ psi, and $P_i = 4.7$ psi, we find that the required area $A = 2.5$ square inches. To provide a factor of safety of two, we would need 5 square inches per cup. For a circular cup, a radius of 1.26 inches is required.

If the metal sheet is to be turned vertically, the coefficient of friction between the cup and the metal must be considered. Sliding will occur between the vacuum cup and the metal unless the friction force is greater than the weight of the object. This force is calculated, as before, by multiplying the pressure differential due to the vacuum by the area of the cups and the coefficient of friction. Metal plates may be oily or dusty, so the friction coefficient may range from 0.1 to 0.7 depending on the situation. Vacuum cups with an area of A, will be able to pick up a sheet weighing W pounds when the coefficient of friction is μ and the pressure differential is p. The following equation may be used to calculate the weight-handling capability of the vacuum pickup. A factor of safety, s, has been included in the equation:

$$W = A\mu ps$$

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A typical multiple vacuum cup pickup is shown in Figure 3.18.

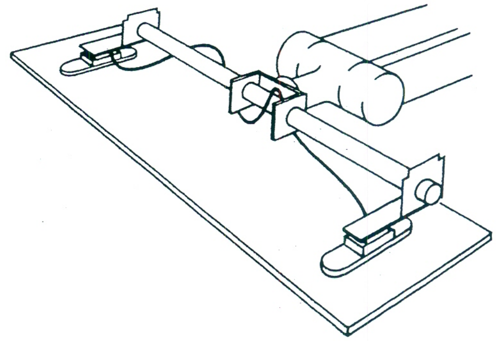


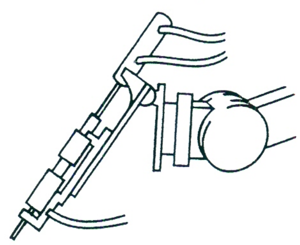
Figure 3.18 Multiple vacuum cup pickup.

Source: Robotics in Practice by J.F. Engelberger, page 52.

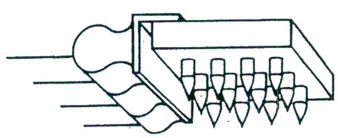
Vacuum pickup is essentially useful for lightweight, thin materials that would otherwise be difficult to handle. It is superior to magnetic pickup even for ferromagnetic materials. It is necessary to consider the surface conditions, however. Oil or dust may make the surface low in friction.

4. Specialized End-of-Arm Tooling

A large variety of specialized toolings may be mounted on a robot wrist. Stud-welding heads and a heating torch are the examples shown in Figure 3.19. Others in common use are arc welding guns, spray paint guns, grinders, drills, and so on.



(a) Stud-Welding Head
Studs are fed to the head from a tubular feeder suspended overhead. Except for the mounting bracket, this could be the same tool used for manual operations.



(b) Heating Torch
A useful task for an industrial robot is to bake out foundry molds. Fuel can be saved because the robot holds the flame where it is most needed as long as it is needed. Bakeout is faster than it would be in a gas oven.

Figure 3.19 Tools mounted on robot wrists.

Source: Robotics in Practice by J.F. Engelberger, page 55.

3.5 Determining Specifications

Now that we have described the mechanical portions of a robot, we can consider the characteristics that must be specified to ensure that the robot can carry out its assigned tasks. In this section, some