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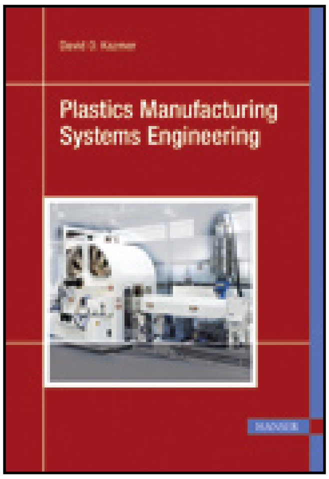

Sample Pages

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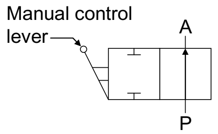
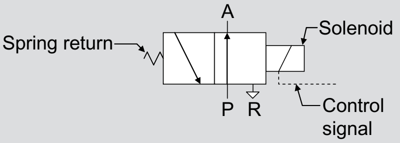
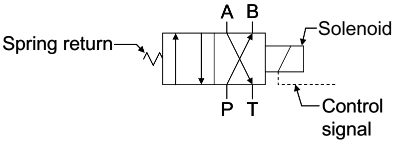
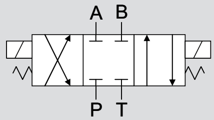
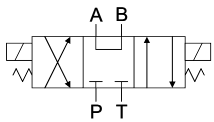
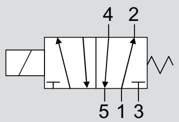
Table 4-6: Common Valve Types

Application	Schematic	Comments
2/2 manual control valve		A manually controlled two position valve used to connect the supply pressure to an actuator port.
3/2 pneumatic valve		A solenoid controlled three port valve used to connect the fluid supply to the port of a one-way actuator.
4/2 valve		A solenoid controlled four port valve used to connect the pressure and return lines to the two ports of a two-way actuator.
4/3 closed centered valve		A four port valve with three positions and a default central position that blocks all ports.
4/3 open centered valve		A four port valve with three positions and a default central position that allows the actuator to move freely.
5/2 valve		A five port valve that connects the actuator to different supply and return pressures.

Both of these 4/3 valve designs are dual solenoid operated, which means that a solenoid must be energized to supply fluid pressure to the actuator. Lastly, 5/2 valves have five ports, which allows the connection of different supply and return pressures to the two actuator ports. As a result, five port valves can allow an actuator to provide very different behaviors in different directions.

Although there are many different valve configurations with respect to number of fluid ports and number of valve positions, there are essentially only two types of valve. Finite position valves have only a set number of positions, such that the valve is either fully closed with no flow passing through the valve or fully open with full flow passing through the valve. Alternatively, infinite position valves permit the valve to assume any number of positions with varying rates of flow through the valve. The design and operation of both types are next discussed.

4.5.1 Directional Valves

Finite position valves typically have only two positions corresponding to full supply or stoppage of fluid flow. The hydraulic pressure relief valve of Figure 4-9 is a finite position 2/2 control valve. When the force from the fluid pressure exceeds the force from the compression spring, the check ball assembly is pushed backwards. Once the check ball is pushed back, the fluid pressure is exerted on the full area of the piston, which causes the piston to fully retract. The fluid flows from the supply line to the reservoir until the supply pressure is reduced and the compression spring forces the check ball to its closed position. As such, this pressure relief valve is known as a finite position valve even though the controlled pressure can be adjusted.

Finite position valves are also known as directional control valves since they typically serve to control the direction but not the exact rate of flow when provided a control signal. For example, Figure 4-16 provides the design of a three port, two position, normally closed solenoid valve [100]. This directional valve could be connected to the pneumatic cylinder of Figure 4-13 or the swivel module of Figure 4-14. In this 3/2 valve design, a compression spring pushes the valve leftwards to seal the pressurized supply fluid from the actuator. Any fluid in the downstream actuator is free to flow from the output port through the valve and back to the return line. When the solenoid is energized, the valve is pushed towards the right to seal off the return line from the supply line and output port. Pressurized fluid then flows through the valve to the output port until the solenoid is deactivated. Figure 4-16 provides some interesting details as to the design of real valves, including the use of a fluid vent between primary and secondary seals to minimize contamination to the solenoid.

The flow rate, Q, passing through a restriction can be well estimated through the orifice equation for turbulent flows with Reynolds numbers above 50,000 [101]:

$$Q = C_d A \sqrt{\Delta P} \tag{4-8}$$

where Q is measured in l/s, A is the constricting cross-sectional area of the valve measured in cm^2, ΔP is the pressure drop of fluid across the orifice measured in bar, and C_d is an experimentally discharge coefficient. The discharge coefficient C_d is approximately 3.8 $l/cm^2bar^{½}s$ for hydraulic fluids and approximately 104 $l/cm^2bar^{½}s$ for air at a temperature of 20 °C.

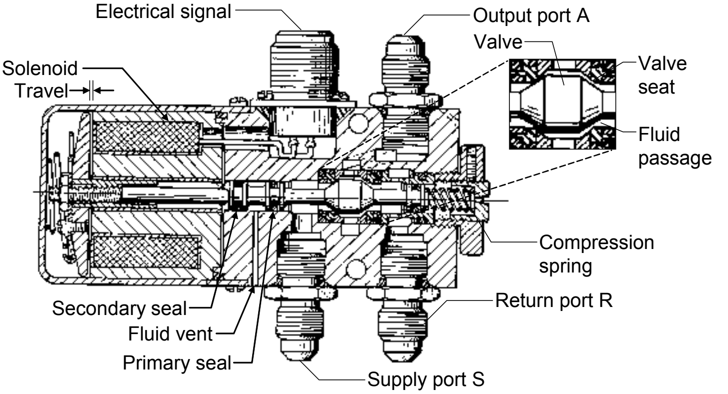


Figure 4-16: Three port, two position, normally closed solenoid valve

Example 4-6: A process engineer finds a directional valve with an orifice radius of 2 mm. Estimate the flow rate for a pressure drop of 6 bar across the valve's orifice.

Solution: The area of the orifice is π (0.1 cm)^2 or 0.13 cm^2. For a 6 bar pressure drop, the output flow rate when the valve is open will be approximately

$$Q = \frac{104\ \text{l}}{\text{cm}^2\text{bar}^{1/2}\text{s}} 0.031\,\text{cm}^2 \sqrt{6\ \text{bar}} = 8\ \text{l/s}$$

Higher flow rates require larger orifices and pressure drops.

4.5.2 Metering Valves

Directional valves are typically used in applications in which the specific velocity of the actuator is not critical and the final position of the actuator is determined through mechanical stops, though exceptions do exist [102]. When the actuator must follow a velocity profile or move to intermediate positions, a closed loop control strategy is commonly employed in which the position of the machinery is monitored with a position transducer. The flow rate to the actuator is then constantly updated through the use of a metering valve that continuously receives control signals from the process controller. Metering valves are also referred to as infinite position valves since the controlling means within the valve can take any position within its range to output a varying flow rate [103].

Common types of metering valves include proportional valves and servo valves. A design of a hydraulic proportional spool valve is shown in Figure 4-17 [104]. As shown in the detailed drawing, the working fluid is supplied at pressure through a port P from a side of the valve body. The valve body contains annuli at each of the port locations to circulate fluid around the spool. The spool itself contains two lands that glide within the bore of the valve body; these lands have small grooves to provide lubrication between the lands and the valve body. The spool and valve body are designed so that the pressure on the faces of the spool valve are balanced within each section of the spool. As such, the spool can be moved with a minimum amount of force.

In this design, two sets of solenoids and springs are used to control the valve spool position. In operation, only one solenoid is energized at a time to pull the spool valve in its direction. Each solenoid has a spring to return the valve spool to its centered position when the solenoid is not energized. This design is "fail safe" since the spool will return to center and block flow to all ports when no power is provided to either solenoid. When the spool valve is moved to the right, a pathway is created from the pressure port to the B port connected to the actuator. As fluid is conveyed to the actuator in a typical system design (refer to Figure 4-1), the actuator's piston or rotor will move and return fluid at lower pressure to the valve's A port. The spool valve is designed so that the movement of the spool to the right also creates a passage connecting the A port to the return port, identified as R or T in most schematics referring to the return or tank lines. While not a necessity of all valves, many valves provide reversible flow control. In a reversible design, moving the spool to the left would create passages from the pressure port to the A port and from the B port to the return port.

The performance of proportional valves has improved with continuous advances in electronics, fluid dynamics, and manufacturing technologies. Proportional valves provide good dynamic

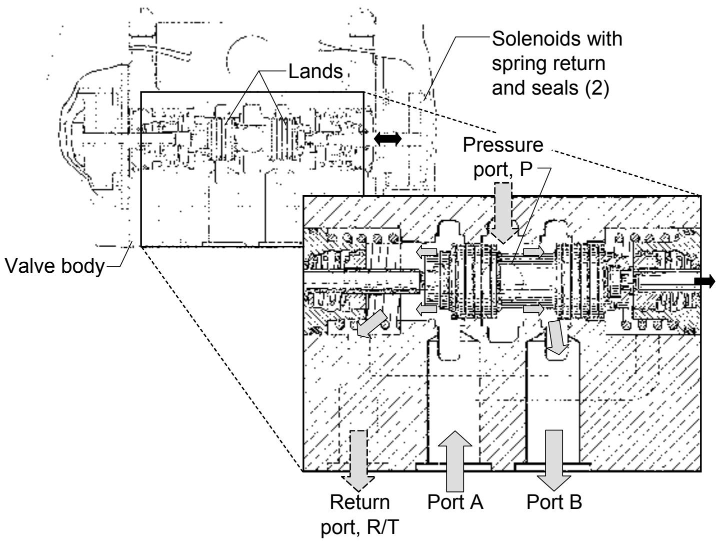


Figure 4-17: Hydraulic proportional spool valve

response in many applications. The primary limitation of proportional valves stems from the trade-off that must be made between the size of the spool and the power required to control the spool position; larger spools will provide higher flow rates but also require more control energy or longer response times. Given that solenoids have very low power density compared to hydraulics, two stage valves use the fluid delivered from a smaller flapper valve to regulate the position of a larger spool. Higher flow rates may be delivered in less time since the flapper valve is very small but yields significant hydraulic power for controlling the primary spool's position.

One two stage servo valve design is shown in Figure 4-18 [105]. In this design, pressure and return ports are connected to the valve bore as in a conventional spool valve. However, the pressurized fluid is also delivered to the outside ends of the spool as well as nearby control nozzles. The internal cavity around the flapper valve is connected to the return port through a drain channel as shown. In operation, a control signal is provided to a torque motor or solenoid. The resulting torque causes the flapper to move towards one of the nozzles. The full or partial blocking of the nozzle causes different pressures in the nozzles and the upstream passages. For example, the flapper in Figure 4-18 has been moved towards the left, which seals the left nozzle from the drain channel and simultaneously connects the right nozzle to the drain channel. As a result, the area to the left of the spool will be at a higher pressure than the area to the right of the spool. This hydraulic pressure difference across the spool will cause the spool valve to move to the right and then operate as previously discussed with respect to Figure 4-17.

The size of the nozzles and flow restrictors in a two stage servo valve design can be used to determine the flow rates and pressure drops that govern the spool position. Ideally, metering valves provide output flow rates in direct proportion to their control signal. To achieve this goal, servo valves are typically designed to deliver zero flow when the spool is centered, but

5.4.4 AC Motor Controls

The speed of an AC motor is a multiple of the AC frequency according to Eq. 5-19 and so can be adjusted across a wide range by changing the AC frequency or number of poles; the speed of the motor can also be controlled to a limited degree by changing the slip, rotor impedance, and excitation voltage. Of all these methods, solid state variable frequency drives (VFD) have become predominant due to their ability to provide excellent speed and torque control [138].

The design of VFD circuits is similar to the pulse width modulation circuit shown in Figure 5-10 to control DC motors. The primary difference is that VFD circuits include additional logic to purposefully time the pulses to constitute new AC waveforms that vary in frequency and voltage. For example, Figure 5-14 provides two AC waveforms that were generated by combining discrete portions of the three phase, 60 Hz voltage. In the figure, the three dashed sinusoidal curves represent the three phases of the AC voltage supplied by the electrical utility. The solid portions of these 60 Hz curves have been provided by a pulse width modulation circuit containing the necessary logic for timing control. Different combinations of the three phases can be used to generate different voltages and frequencies, such as the 45 Hz and 36 Hz waveforms represented by the thicker traces. These supply waveforms are suitable for use in AC induction motors when used in conjunction with capacitors and other power conditioners to remove undesired components.

Variable frequency drives may be implemented in either a closed or open loop mode. In an open loop mode, the voltage and frequency is provided from the VFD to the AC motor.

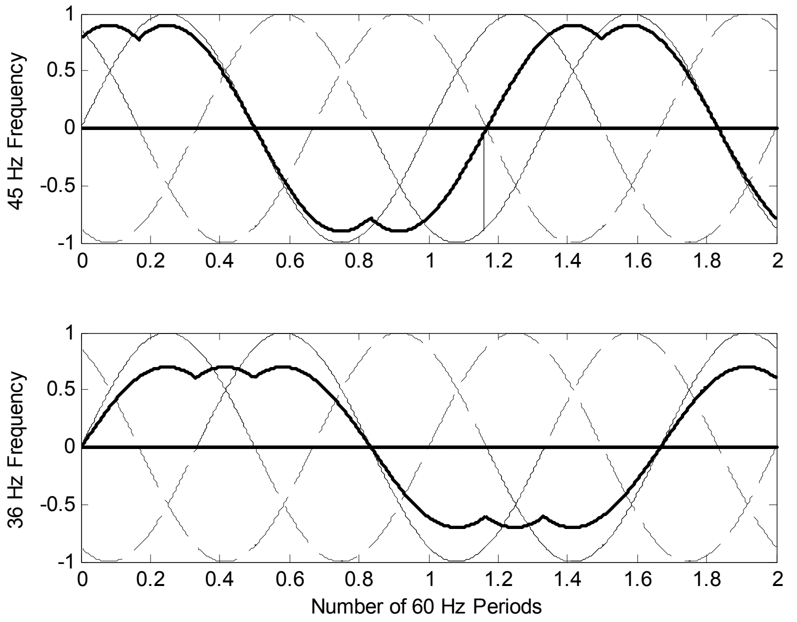


Figure 5-14: AC voltage waveforms generated by combining AC phases

Variations in the imposed mechanical load on the rotor will cause slip and different motor rotational speeds. In a closed loop mode, the rotational speed of the motor is monitored and used to update the frequency and voltage supplied from the VFD. In this manner, AC induction motors can be used to provide high torque and accurate speed control across a wide range of output speeds (typically from 5% to 100% of the rated motor speed). Variable frequency drives can be implemented to also control the voltage supplied to the motor, as implied by the decreasing magnitude of the output waveforms in Figure 5-14. Voltage control with VFDs is useful for controlling output motor torque, especially at low speeds, to avoid excessive in-rush currents as well as undesired acceleration. The torque speed behavior of an AC induction motor is plotted in Figure 5-15 using the prior analysis for different voltages and frequencies from a VFD. The voltage must decrease in proportion to the frequency to provide the same peak output torque according to Eq. 5-25.

One widely cited deficiency of AC motors is their low starting torque and high in-rush currents required to start the rotor moving. The implementation of variable frequency drives resolves these limitations by providing a low starting voltage and frequency for manageable electrical loads and smooth acceleration. The cost of variable frequency drives has been a barrier to widespread adoption, but these costs are decreasing and often more than offset by the increased efficiency of AC motors as well as related energy savings. For example, AC motors with variable frequency drives are being widely adopted for to vary the output from hydraulic pumps and thereby provide highly energy efficient hydraulic plastics machinery. As another example, AC motors with variable frequency drives can be used to drive blowers and fans at fractional speeds when demand is low. To motivate the implementation of energy efficient systems, electric utilities and governments sometimes provide rebates or tax incentives that reduce the initial investment of variable frequency drives.

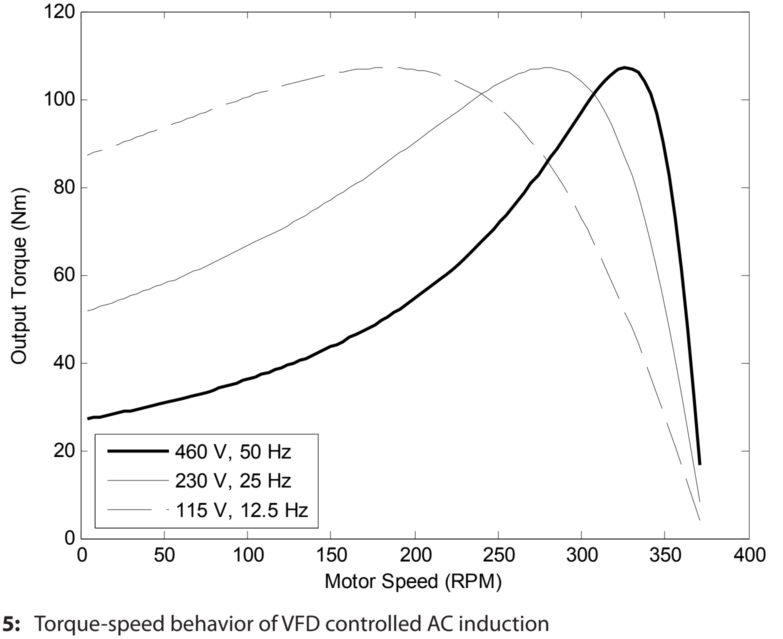


Figure 5-15: Torque-speed behavior of VFD controlled AC induction

5.5 Other Motors

The previously discussed DC and AC motors are the primary movers in most plastics industry applications. Still, there are many other types of electric motors, including variable stepping motors, linear motors, piezoelectric motors, and others. The purpose of this section is not to provide a detailed analysis of these less commonly used motors, but provide an introduction so that the reader can understand their potential use in plastics manufacturing systems.

5.5.1 Stepper Motors

As its name implies, a stepper motor is an electric motor that moves the rotor by one mechanical step each time the motor is provided an electronic signal. There are many different kinds of stepper motors, but the most common types are:

- permanent magnet stepper motors, having rotors consisting of permanent magnets,
- variable reluctance stepper motors, having rotors consisting of soft iron with high permeability, and
- hybrid stepper motors having multiple stacks of rotors with different magnetic poles along the axis of the motor.

Each type of the stepper motor is operated in a slightly different manner and provides different stepping, torque, and speed characteristics.

The design of a hybrid stepper motor is shown in Figure 5-16 [139]. This design consists of four sets of toothed poles that provide a magnetic field to the teeth when the corresponding coils are energized. Two toothed rotors are separated along the axis of the motor by a permanent

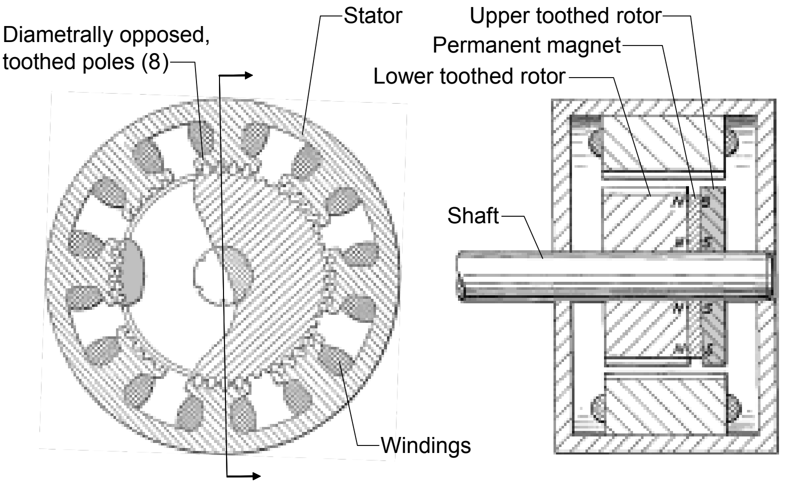


Figure 5-16: Design of a hybrid stepper motor

magnet. Since the rotors have high permeability, this arrangement serves to provide different polarity to each of the rotors. In this particular design, the two rotors are provided with 50 teeth, spaced in increments of 7.2°. The two rotors are angularly offset by 3.6° so that the teeth on the upper and lower rotors are staggered and do not directly overlap. In operation, each set of poles on the stator are sequentially energized to attract a nearby set of teeth on one of the rotors. Since the angular position of the stators are also offset by design, an angular resolution of 1.8° can be provided per step.

The design of Figure 5-16 would also be feasible with a single toothed rotor albeit with reduced angular resolution. In such a single stack design, the number of steps per revolution, n, is related to the number of stator poles, m, number of electrical phases, p, and the number of rotor teeth, t:

$$n = m\,p\,t \qquad \text{5-28}$$

For example, a common stepper motor design might have a fifty toothed gear with two pole pairs operating in two phases. This design results in 200 steps per revolution of the geared rotor, or a 1.8° step. Compared to other types of motors, stepper motors have relatively low torque due to their use of multiple alternating poles to step the motor. Since the poles do not simultaneously attract the rotor's teeth, a lower output torque is provided than would be possible with other motors of similar size.

Figure 5-17 provides the torque and power behavior of a typical stepper motor, the Aerotech model 1010SM [140]. The motor torque is high and nearly constant at low speeds, and then

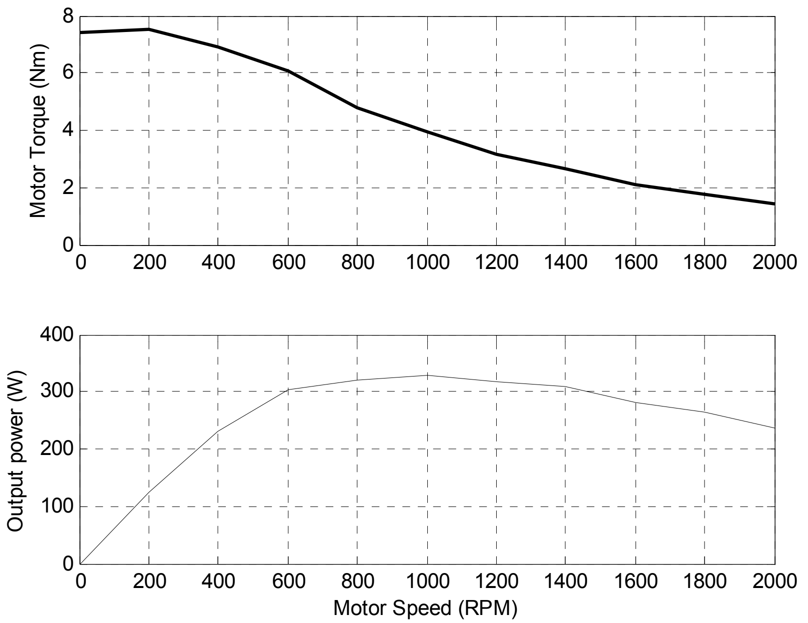


Figure 5-17: Torque-power behavior of a typical stepper motor

12.1 Process Capability Assessment

Given that all manufacturing processes exhibit variation, the capability of the process is usually assessed relative to specification limits. There are several common methods used to assess process capability [271–273], most of which assume normal statistics. The underlying framework for these process capability assessments is provided in Figure 12-2. In considering the process capability, the distribution of the process data is considered relative to the lower specification limit, *LSL*, and the upper specification limit, *USL*. If a normal distribution is assumed with a mean, μ, and a standard deviation, σ, then the percentage of manufactured defects can be readily calculated along with the yield of acceptable product. Several other process capability measures are common in the manufacturing industry, including the process capability index, defects per million opportunity, and process capability roll-up. Each of these measures is next discussed.

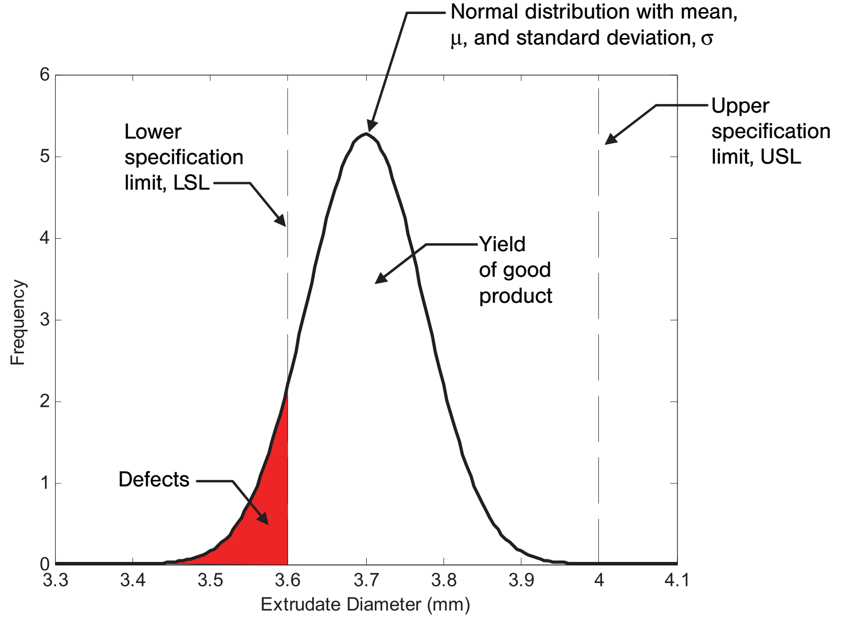


Figure 12-2: Process distribution relative to specifications

12.1.1 Yield Estimates

The yield is defined as the fraction of the manufactured products that are acceptable. If a normal distribution is assumed, then the yield can be mathematically defined as the integral of the normal probability density function between the lower and upper specification limits:

$$\text{yield} = \int_{LSL}^{USL} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] dx \tag{12-1}$$

Applying the limits of the normal cumulative distribution function provides a direct estimation of the yield:

$$\text{yield} = \frac{1}{2}\left[1 + \text{erf}\left(\frac{USL - \mu}{\sigma\sqrt{2}}\right)\right] - \frac{1}{2}\left[1 + \text{erf}\left(\frac{LSL - \mu}{\sigma\sqrt{2}}\right)\right] \qquad \text{12-2}$$

where μ is the mean, σ is the standard deviation, and erf is the Gaussian error function. The yield will approach 100% when the standard deviation is small and the mean is centered between the lower and upper specification limits.

Example 12-1: An extrusion process provides an extrudate with a mean diameter of 3.700 mm and a standard deviation of 0.076 mm. Estimate the manufacturing yield if the lower and upper specification limits are 3.6 and 4.0 mm, respectively.

Solution: The yield may be estimated by numerically integrating the normal probability function of Eq. 12-1 or by evaluating the limits of the normal cumulative distribution function of Eq. 12-2 with the Gaussian error functions. The following Matlab code uses the `normcdf` function to implement Eq. 12-2:

```
d_mean=3.700;                    % Mean [mm]
d_std=0.076;                     % Standard deviation [mm]
LSL=3.6;                         % Lower spec limit [mm]
USL=4.0;                         % Upper spec limit [mm]
yield=normcdf(USL,d_mean,d_std)-normcdf(LSL,d_mean,d_std)
```

The estimated yield is 90.58%. Most of the defects are associated with the extrudate diameter being too small as shown in Figure 12-2. While many plastics manufacturing processes operate with a yield around 90%, this yield in an extrusion process would likely be unacceptable since the defective product is continuously interspersed with acceptable product. Removal of the defective product would require cutting the extrudate into undesirably small lengths or otherwise rejecting significant amounts of product. The yield can be improved by shifting the process to increase the diameter or otherwise reducing the process variation.

12.1.2 Process Capability Indices, C_P and C_{PK}

The yield calculation is highly useful but is difficult to calculate without access to a mathematical library. In addition, the interpretation of the yield estimate becomes less intuitive as the yield approaches 1. A yield of 99.9999% will require a process that is much more robust than a process providing a yield of 99.7% even though the yield is less than 0.3% different. For these reasons, the process capability indices, C_P and C_{PK}, have been defined [272]. The process capability index is defined as the breadth of the specification limits divided by six standard deviations:

$$C_P = \frac{USL - LSL}{6\,\sigma} \qquad \text{12-3}$$

The process capability index, C_P, was designed such that a value of 1 is considered standard. If the process is centered between the upper and lower specification limits, then three standard deviations of process variation exist between the mean and each specification limit, such that the yield is 99.7%.

The primary issue with the process capability index is that it assumes that the process can be centered between the upper and lower specification limits. If the process is not centered, as is the case with the extrudate diameter of Figure 12-2, then the process will provide a much lower yield than suggested by the process capability index. In such cases, the asymmetric process capability index, C_{PK}, should be used:

$$C_{PK} = \min\left[\frac{\mu - LSL}{3\sigma}, \frac{USL - \mu}{3\sigma}\right] \tag{12-4}$$

The asymmetric process capability index also has an advantage in that it can be used for one sided specifications, in which only the lower or upper specification limit is defined.

Example 12-2: Calculate the process capability index, C_P, and asymmetric process capability index, C_{PK}, for the previous extrudate example.

Solution: The two indices are calculated in the following Matlab code:

```
C_P=(USL-LSL)/(6*d_std)
C_PK=min([(USL-d_mean)/(3*d_std) (d_mean-LSL)/(3*d_std)])
```

The resulting C_P and C_{PK} values are 0.877 and 0.439, respectively. The C_P value of 0.877 suggests a manufacturing process with a nearly standard quality level. However, the shift of the mean towards the lower specification limit results in a much lower C_{PK}.

Table 12-1: Yield as a Function of Process Capability

Process capability index, C_P	Yield (%)	Defects per million opportunity
0	0	1,000,000
0.167	38.29	617,100
0.333	68.27	317,300
0.5	86.64	133,610
0.667	95.45	45,500
0.833	98.76	12,420
1.0	99.73	2,700
1.333	99.95	63
1.667	99.99	6
2.0	99.9999	2
2.5	99.99999999	0.0001
3.0	~1	~0

The yield and process capability indices are directly related through the normal cumulative distribution function. If the process is centered, then the yield can be estimated from the process capability index as:

$$\text{yield} = \text{erf}\left(\frac{3 \cdot C_P}{\sqrt{2}}\right) \tag{12-5}$$

The expected yields for processes of varying capability are listed in Table 12-1. It is observed that yield increases significantly as the process capability increases from zero and then approaches 100% at process capabilities above 1. Given normal statistics, the yield provides 99.9999%, sometimes referred to as "six nines" at a process capability index of 2. This quality level is the goal of many Six Sigma initiatives as discussed in the next section, and in theory should result in only 2 defects per million opportunities.

12.1.3 Six Sigma

"Six Sigma" is a quality control initiative developed by Motorola [274] that increasingly refers to corporate initiatives with multiple objectives and a broad range content generally directed to corporate competitiveness [275–277]. However, the most fundamental tenet of Six Sigma, from which the name is derived, is that six standard deviations of process variation should be maintained between the process mean and the closest specification limit. As shown in Figure 12-3, *LSL* and *USL* correspond to the lower and upper specification limit on a critical quality attribute while μ and σ represent the observed mean and standard deviation. Statistically, only two defects per million opportunities (DPMO) would occur if the six sigma criterion was satisfied.

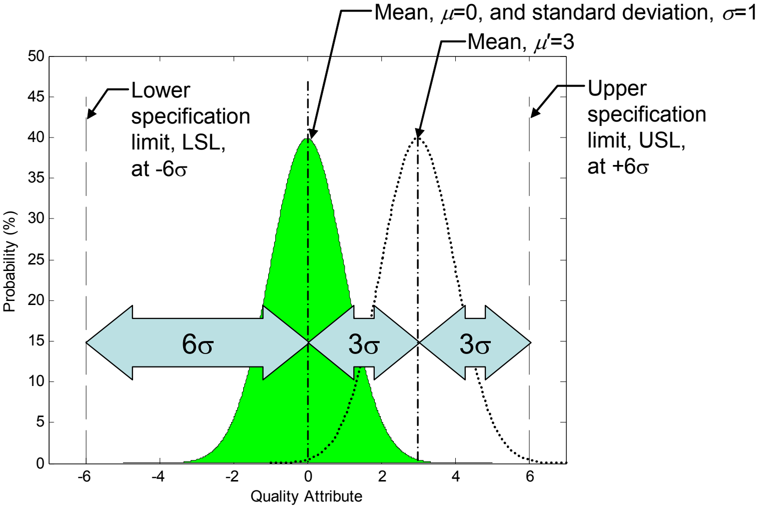


Figure 12-3: Six sigma concept

Historically, there are two somewhat different motivations for achieving Six Sigma [274]. First, it has been argued that Six Sigma is necessary in large systems, such as semiconductors, that internally contain many opportunities for defects. Since the system may fail with any given component, reliability theory states that the DPMO must be extremely low to achieve reasonable yields in production, typically greater than 95%. An alternate motivation in Six Sigma pertains to the product development process and ensuring long term stability in the product quality. With six standard deviations between the process mean and the closest specification limit, a long term shift of three standard deviations in the process mean from μ to μ' can occur while still ensuring three sigma for short term, random variation as shown in Figure 12-3. As such, a 99.7% yield should be achieved in 99. 7% of applications exhibiting 3σ short term variability.

Since its inception, Six Sigma has drawn upon many previously established methodologies including the design, measure, analyze, improve, control (DMAIC) process [278]. Another significant underpinning of Six Sigma is the capability roll-up for manufacturing processes that have multiple specifications. In a capability roll-up, the defects per million opportunity are individually calculated for each specification according to the previously defined normal statistics. The defects per million are then summed to provide the total number of defects expected per million opportunities, *DPMO*. These calculations for the total *DPMO* are expressed by the equation:

$$DPMO = \sum_{i=1}^{m} 1 \cdot 10^6 \cdot \left[1 - \mathrm{erf}\left(\frac{3 \cdot C_{P,i}}{\sqrt{2}}\right)\right] \qquad \text{12-6}$$

where $C_{P,i}$ is the process capability associated for the i-th of m specifications. After the total DPMO is calculated, the yield can be estimated as:

$$\text{yield} = \left(1 - \frac{DPMO}{1 \cdot 10^6}\right) \qquad \text{12-7}$$

The rolled up process capability index can also be calculated as:

$$\bar{C}_P = \frac{\sqrt{2}}{3}\,\mathrm{erf}^{-1}(\text{yield}) \qquad \text{12-8}$$

For a process to qualify as six sigma, the rolled up process capability index must be two or greater.

Example 12-3: A stretch blow molding process has three specifications. In characterizing the process variability, the blow molder has evaluated process capabilities for thickness, clarity, and inflation equal to 1.1, 1.2, and 1.5. Estimate the total number of defects per million opportunities and the rolled up process capability index.

Solution: The solution is implemented in the following Matlab code. The analysis indicates there are 967 thickness defects, 318 clarity defects, and 7 inflation defects per million opportunities that total 1,292 defects per million. The rolled up process capability jointly considering all three specifications is 1.073.

14.3 Robotics

Process automation can be implemented by the custom design of plastics processing machinery and associated molds/tools as described Section 14.5. However, it is equally as common for process automation to be achieved by the incorporation of robotics to augment or replace human operators. It may seem surprising that nearly 25% of all robots are used in plastics manufacturing, with the majority of those robots used for injection molding applications [374]. The reason is that plastics manufacturing processes support high production volumes with short cycle times, so the use of robotics for parts handling and assembly reduces costs while also relieving operators of repetitive, meaningless tasks.

The most common application for robots in plastics manufacturing, by far, is for part removal. The reason is that the use of robots for parts removal provides for faster and more consistent cycle times since

1. the safety gates remained closed,
2. the robot can move along with other machine elements, and
3. the robot can move more quickly than a human operator.

In addition, the use of robotics for part removal reduces likelihood of damage due to uncontrolled ejection and also supports subsequent part placement and assembly operations. The second most common application for robotics is for the positioning of inserts or labels into the mold prior to processing. Other common secondary operations include trimming, degating, painting, assembly, welding, and metrology, among others.

There are many different types of robots that have been developed in research labs and implemented in practice. From an academic perspective, robots are typically referred to by their coordinate systems with common types including cylindrical, Cartesian, and polar. From an industrial perspective, robots are more often referred to by their function with typical types including sprue pickers, gantry, SCARA, and fully articulated robots. Each of these types will be discussed along with some concepts related to end of arm tooling.

14.3.1 Sprue Pickers

The sprue picker is a simple pick and place robotic device with a common design [375] shown in Figure 14-7. The gripper is located at the end of the robot arm and is intended to grip a central sprue in an injection molding process; the gripper is typically positioned with two actuators that together yield a cylindrical work envelope. In this design, a pneumatic cylinder moves the gripper in and out along its axis, while a pneumatic motor rotates the gripper about the robot's horizontal axis. The simplest sprue picker can be operated without a feedback controller by using mechanical stops to limit the travel of the robot. Each of the actions to rotate, extend, grab, retract, rotate, and drop are readily implemented using ladder logic upon receipt of the molding machine's mold opening signal.

The pneumatic system design shown in Figure 14-7 has limited performance since the pneumatic actuators are relatively slow, low force, and have limited position control. By

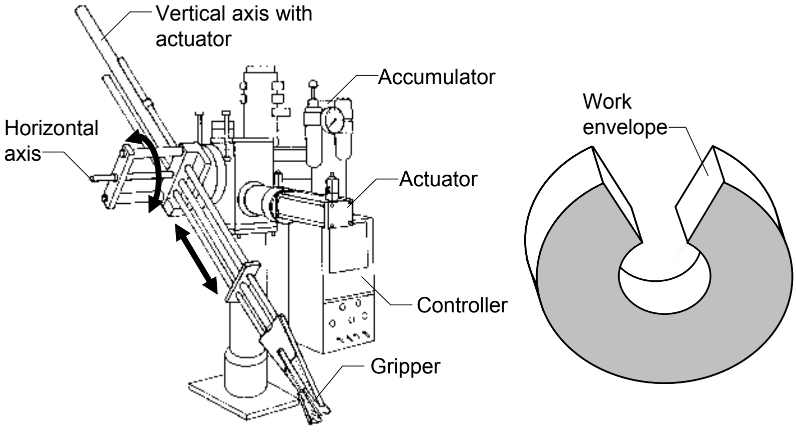


Figure 14-7: Sprue picker robot design and work envelope

comparison, hydraulic and servomotor driven systems will increase cost but significantly improve the dynamic response and functionality. Typical specifications include a part take-out time on the order of 1 s, a cycle time of 4 s, and a payload of 3 kg. Smaller sprue pickers tend to have a reduced range of motion with faster processing times but also smaller payloads.

Modern sprue pickers also include position sensors and fairly advanced controllers that can be programmed by manually moving the sprue picker to follow arbitrarily complex position profiles, and then adjusting the timings to coordinate the robot with the molding operation. Modern robot controllers can also interface with the machine controller to ensure that the clamp does not close the mold until the sprue picker has moved (or is moving) away. Finally, a modern sprue picker can detect the presence of the sprue using mechanical feedback from the point of pick-up until drop off. In case of a blocked sprue or dropped part, the sprue picker can halt the molding operation and provide an alarm with the relevant data.

Example 14-5: A plastics molder operates a 100 ton electric molding machine that is operated at a rate of $80/hr. The use of a sprue picker is suggested to provide a 5% productivity improvement due to cycle time reductions and increased process consistency. Estimate the annual savings of the sprue picker if the machine is operated 4,000 hr per year.

Solution: The total income from the molding machine is the $80/hr operating rate times the machine usage of 4,000 hr/yr. This equals an annual income of $320,000. If the 5% productivity improvement was realized, then annual savings of $16,000 would be achieved. The cost of a sprue picker for a 100 ton machine is on the same order of magnitude, so the sprue picker could pay for itself within a year. There are two potential issues, however. First, the molder will only recover the savings if the molding machine is fully utilized. The savings will not be nearly $16,000 if the machine is idle or there are not additional jobs to occupy the machine's new availability. Second, the savings assumes that the sprue picker is used on every application and does not incur additional delay or costs due to programming or maintenance. The successful implementation, even for a robot as simple as a sprue picker, will require an internal champion to leverage the capabilities of the robot in multiple applications.

14.3.2 Traversing Robots

Traversing robots use a Cartesian coordinate system to move in three dimensions. When enclosed above the workspace by a rigid frame as shown in Figure 14-8 [376], the traversing robot can lift medium to heavy loads and is referred to as a "gantry robot". The design and operation is simple to understand, with each motion axis provided by a rack with uniformly spaced teeth. In operation, geared servomotors drive a pinion at moderate torque and speed to cause the carriage to traverse the rack. The design of Figure 14-8 uses four servomotors in total: two driven in parallel to traverse the *y* axis and one for each of the *x* and *z* axes. While traversing robots are more expensive than sprue pickers, they remain relatively inexpensive compared to other robot types. A significant benefit of gantry robots is that their design places the robot off the manufacturing floor, which not only saves space but also allows the robot head to traverse above the machine platens and tie bars.

While the design of Figure 14-8 uses a fully supported bridge with four cross rails, many traversing robots use a cantilever beam design mounted to the frame of platen of the machine. The bridge extends in an unsupported fashion beyond the side of the clamping unit. The robot head accesses the plastic parts on the parting plane of the mold, and then traverses out of the clamping unit to place the parts on a conveyor or in a storage bin for subsequent handling. Cantilever style traversing robots are sufficiently stiff for handling the robot head, end of arm tooling, and plastic parts, but are not suitable for lifting molds. For example, the AEC 101-F3SV [367, 368] is suitable for use with 150 to 300 ton molding machines and has an optimum payload of 8 kg, including the end of arm tooling. Traversing robots provide part take out times on the order of 1.5 s while a full cycle including the traversal of the bridge, part placement, and reset typically require 10 s.

Traversing robots can be actuated by any of the means discussed in Chapters 4 and 5. The most common methods include pneumatics, AC induction motors, and DC motors with a drive system similar to that shown in Figure 14-8. While these different actuators provide similar operating speeds and forces, electrically driven systems will tend to be quieter and provide

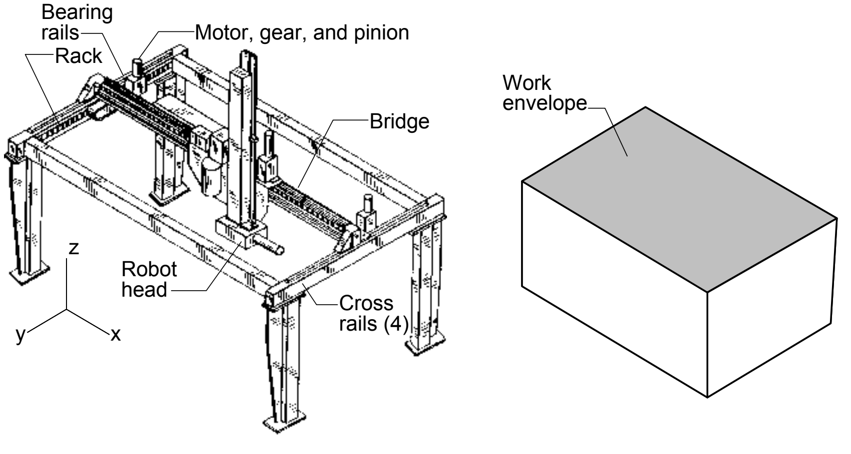


Figure 14-8: Gantry robot design and work envelope

smoother operation and more accurate control; some traversing robots use linear motors as described in Section 5.5.2 to provide motion without any gearing that are suitable for clean room applications. As may be expected, robots with multiple control axes and many program steps rely on closed loop control often implemented with programmable logic controllers (Section 9.1.1) having their own LCD panels and operator interface. Positioning accuracy of servo driven traversing robots is on the order of 0.1 mm.

When selecting a traversing or gantry style robot, it is important to verify mounting, clearance, and range requirements. These robots are often mounted to the top of one of the machine platens, which can interfere with mold changes. The vertical axis can extend far above the height of the machine, so ceiling clearance should be verified. Finally, the robot head should be able to traverse across a range sufficient to operate with any molding application that may be performed with the machine installation. Robots are sometimes purchased for a specific molding application, only to be later discovered insufficient in other molding applications [363].

14.3.3 SCARA Robot

SCARA is an acronym derived from selective compliance assembly robot arm. One design is shown in Figure 14-9 [377]. The classic SCARA robot has a primary link that can rotate about the robot's vertical axis with a second link that can rotate with respect to the end of the first link. Both links can move up and down with the main body of the robot. Compared to traversing robots, the more compact and rigid SCARA designs allow for more rapid operation with higher payloads. For example, the Denso HM-4AA03G has a 0.31 s cycle time with a 1 m

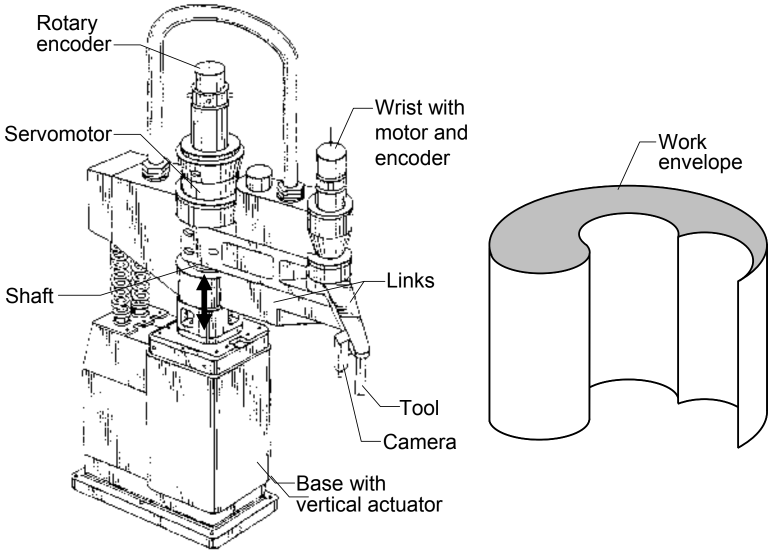


Figure 14-9: SCARA robot design and work envelope

reach, 20 kg payload, and a 0.025 mm positioning accuracy [378]. Their closed joint design also makes them more suitable for clean room environments than linear traversing robots of the previous section.

While SCARA robots are faster and cleaner than the previously described systems, they do have several disadvantages. First, they most often use a pedestal mount next to the machine and so require side access to the mold's parting plane. This installation can be problematic since

1. safety gate must be removed or modified to provide access for the robot in and out of the machine,
2. the robot's placement blocks operator access to the mold, and
3. the robot can interfere with mold cooling lines and positioning of other devices such as mold temperature controllers, conveyors, etc.

For these reasons, SCARA robots are not as common in the plastics industry as traversing robots. However, SCARA robots should be considered in high volume applications where cycle time, accuracy, and cleanliness are vital. While SCARA robots may seem complex due to their geometry and associated work envelope, the transformation to the Cartesian coordinate system is internal to the controller so the user interface and end of arm tooling operate just as a traversing robot.

14.3.4 Fully Articulated Robots

A significant issue with both of the previously discussed traversing and SCARA robot designs is their lack of degrees of freedom. Specifically, each of these robot designs has three degrees of freedom allowing movement in the x, y, and z directions. End of arm tooling can often be provided with an additional degree of freedom that allows the manipulator to change its orientation relative to the vertical axis of the robot. However, these robots have limited flexibility and reach given the size of their design.

To provide greater range of motion and more flexibility in application, fully articulated robots have been designed that mimic human limbs and joints. One design is shown in Figure 14-10 [379]. The robot includes a base that swivels on the vertical axis, an upper arm that rotates at the waist, a forearm that rotates at the elbow, and several joints for rotating the wrist. In total, the robot has six degrees of freedom that allow the end of arm tooling to not only reach any point within a spherical work envelope but also present the end of arm tooling from any direction. Their articulated design also provides a high degree of cleanliness and excellent dust/mist resistance.

Articulated robots are not quite as stiff or fast as SCARA designs, but are faster and similarly stiff as Cartesian traversing designs. For example, a Denso VM-6083D articulated robot has a reach of 1 m (range of 2 m), a cycle time of 0.9 s, a payload of 10 kg, and a positioning repeatability of 0.05 mm. Given their positioning flexibility, articulated robots can be mounted to the top or side of the platen to avoid issues with floor mounting adjacent to the floor as in the SCARA design. Complexity of programming is also reduced with modern user interfaces. While articulated robots have significant potential in plastics manufacturing, their penetration into the industry has been largely limited by their cost.

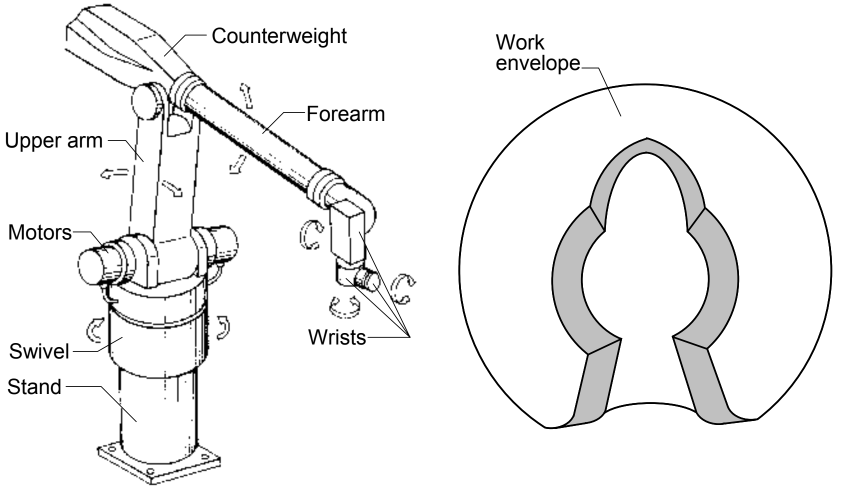


Figure 14-10: Articulated robot design and work envelope

Example 14-6: A plastics molder operates a 200 ton electric molding machine that they operate at a rate of $130/hr. They are tying to choose between a $25,000 Cartesian traversing robot with a part take-out time of 1.3 s and a $70,000 articulated robot with a part take-out time of 0.7 s. Assuming that the average cycle time for the machine is 30 s and the part take-out does constrain the cycle, determine which robot is most cost effective.

Solution: The difference in take-out times between the two robots is 0.6 s. This corresponds to a productivity increase of 2% for their average molding application. A 2% productivity increase corresponds to a potential cost savings of 2.6 $/hr. Given the $45,000 upcharge to use the faster articulated robot, the payback period is on the order of 17,300 operating hours. This payback period corresponds to roughly 2 years of operation for 24 hours per day, 365 days per year. The realized payback period would likely be much longer when considering actual operation times as well as training and maintenance costs. For these reasons, the articulated robot is unlikely to be selected based solely on cycle time savings but may still be preferable for other automation capabilities.

14.3.5 End of Arm Tooling

End of arm tooling is used to interface the robot head with the plastic part and other auxiliary equipment [380]. To a large extent, the end of arm tooling determines the functionality of the robot as well as its repeatability. As such, end of arm tooling can be a barrier to the successful implementation of robotic systems. The single most common end of arm tooling is a gripper that can be used to grab sprue, runners, or other areas of the molded product. One gripper design [381] is shown in Figure 14-11. This and many designs use a pneumatic actuator to drive the gripper mechanism. In this design, a one-way cylinder (similar to Figure 4-13) pushes the piston rod and attached wedge towards the gripper when provided fluid pressure. The wedge drives the rear portion of the fingers outward so that the fingers pivot and close. After the robot moves the gripper and secured part to a different location, the air pressure is released and the compression springs return the fingers to their open position. While not