Introduction to Designing Machine Control Systems, Part 1

by

Ed Thompson
Introduction:

This course is the first part of a two part series, as an introduction for designing Machine Control Systems for the design Engineer. Part 1 presents overall system design issues up to Control Cabinets. Part 2 presents aspects of inside of the Control Cabinet design and beyond.

While this presentation is not comprehensive, the goal is to provide enough background for further in-depth studies in a wide range of related topics. The reader should have at least a working understanding of electricity.

The three major goals for every control system should be safety, reliability, and the ease of troubleshooting. To meet these goals, seven basic steps (see outline below) are presented to help guide the design engineer through the design and implementation of Control Systems.

Disclaimer: This course is not intended to provide an in-depth treatment of the subject matter or to provide engineering advice applicable to specific designs; you therefore should consult with appropriately qualified, licensed engineer/s to evaluate how applicable codes, regulations, rules, statutes and practices that may apply to your particular project/s.

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1 Process I/O Diagrams:

The importance of a good Process I/O diagram is extremely valuable as it can be used as the foundation for most of the tasks required to design Control Systems. To begin with, the activities and questions that are needed to develop a good Process I/O diagram are also very helpful towards accurately defining a detailed understanding of the deliverables of a project. One of the most important results of developing the Process I/O diagram is that as various options and details are discussed, all participants, especially the end user/client come to have a clear understanding of how the completed project will operate.

Once the Process I/O diagram is completed, every function and motion of the process/machine should be schematically represented. The diagram will be a simplified "picture" that can then be used to design the Wiring Schematics. This in turn can be used to develop the Control Panel Assembly. The Process I/O diagram will ultimately be helpful for programming the Programmable Logic Controller (PLC). The importance of a good Process I/O diagram cannot be over emphasized as it will also be a valuable tool during the installation, startup, wiring, programming, writing the maintenance manual/s, and later for system troubleshooting (Please refer to the sample diagram below).

The idea of "Process I/O" diagrams is not to re-invent "the wheel", but rather is the logical extension of the classical Piping and Instrumentation (P&I) diagram. P&I diagrams are typically comprised of varieties of valves, tanks, pumps, and various sensors, etc.
Diagram A, is an example of a P&I diagram.

The value in a good P&I diagram is that the "flow" of the process can be clearly understood, showing how pumps, valves, and various sensors need to and are coordinated together. The Process I/O diagram has similar values.

Standard P&I schematic symbols are a valuable resource and are well established. ISO 14617 and ANSI/ISA S5.1 are good sources of standard symbols. However, regardless of if symbols are standard or custom; all Process I/O drawings should have a "key" or "Legend" that defines all of the symbols used.
Diagram B: Example of P&I Diagram Legend.

As projects become more, "mechanical" and less "process" in nature, standard P&I symbols will probably not be available. Some examples are; an automatic screw head, a rotary index table, a slide positioned by a lead screw, and even a simple cylinder. However, with a little creativity it is not difficult to capture the "essence" of mechanical devices with custom symbols. Below are some samples:
Diagram C, Examples of Custom Mechanical Schematics.

**Basic Cylinder:** The de-energized cylinder is shown retracted with a sensor on each end of the stroke. Note, for simplification, sensors are represented by a simple "box".

**Lead Screw Movement:** Motor, M2 causes the load to move left and right. The symbol is for a stepping motor where Y2 produces a single step and Y3 determines the direction. Stepping motor systems can accurately determine the distance and direction. S1 and S2 are end of travel sensors. S3 is the home sensor for setting the "zero" position of the slide.

**Rotary Index Table:** The table rotates when Y0 is energized. X7 will indicate when the table reaches the next position. Three "steps" are needed to consistently operate most rotary index tables. 1) Y0 is energized until X7 becomes false. 2) Y0 remains energized until X7 becomes true. 3) Y0 is immediately de-energized when X7 becomes false. At this point the table should be accurately positioned.

**Part Feeder:** Vibratory Part Feeders typically have their own internal controls. It is usually necessary to detect when a part is at the end of the feeder and ready to be picked-up for use. There may be a number of functions internal to a function, but if they are transparent to the main control, only the interface I/O needs to be identified. In this case, the part available is all that is needed. There may be a completely separate Process I/O diagram provided by the equipment provider that indicates how the internal controls to the unit operate.

**Cylinder & Gripper:** This illustrates two functions, a gripper and the up-down cylinder.
The lift cylinder is similar to "Basic Cylinder" described above. The gripper is using a dual coil solenoid valve. Coil Y5 closes the Gripper and Coil Y6 opens the gripper. The reason why a dual acting coil is used is to maintain grip of the part in the event of an E-Stop event or other similar situation where the "logic" to the gripper may be temporarily lost. S10 and S11 detect if the gripper is open or closed.

Instead of using the term "P&I diagram", the term "Process I/O diagram" is presented for projects which are mostly comprised of custom mechanical symbols with little or no tanks or piping. What these diagrams are called is up to the design engineer, and their title is not what is important. However, these diagrams are extremely helpful and therefore a good diagram should be developed with a symbol legend for every control system.

Piping and Instrumentation diagrams are relatively easy to visualize because the "flow" of the process is usually obvious. Typically, some type of fluid or material originates from a source, which is moved through various process steps (often times a tank) until the finished product is delivered to the output of the process.

In P&I diagrams, most functions occur within various types of tanks. Heating/cooling, mixing, and blending are typical examples. However, in Process I/O diagrams there is an infinite number of types of operations that can be used to describe the various functions. Terms such as: "sub-processes", "motions", "axis", and others terms are commonly used. For clarity, the term "function/s" will be used for this discussion.

For Process I/O diagrams, functions can be heating, cooling, drying, mixing, or the result of hydraulic or pneumatic actuators, or any number of motions that are the result of motors through slides, lead screws, or belts.

Some "functions" may be the result of complex pieces of equipment, such as rivet heads and rotary index tables, etc. In some situations it is important to have a Process I/O diagram for the internal functions of machine modules while others, all that is needed is the interface I/O for how the machine module is connected to the main system. The primary consideration for determining more detailed information is the extent of the modularity. If it is expected to replace the entire unit upon malfunctions, fewer internal details will be needed. However, if extensive internal troubleshooting of a module is expected then more detail should be illustrated in the Process I/O diagram.
For larger projects, it may be appropriate to have a Process I/O diagram for each of the major sections of a system. Sometimes it is helpful to develop an Arrangement block diagram that shows how the various sub-sections are related together. One example of this would be a process where a number of individual machines would be arranged along a conveyor. In this case a single Process I/O diagram is not always appropriate. An Arrangement diagram can be very helpful to show how the sub-machines are arranged along with the control and communications signals between the various machines. Arrangement Process I/O diagrams should also define appropriate numbers for each of the machine elements. These numbers would then designate the individual Process I/O diagrams for each of the machines along the conveyor. Many processes can be described on a single Process I/O diagram; however, with the use of Process I/O Arrangement diagrams the size of processes that can be diagramed is unlimited.

Unlike P&I diagrams, for mechanical systems, the "flow" of the process is not always so obvious. The key is to identifying the "flow" is to follow the movement of the "primary" part. The primary part may be a frame or an individual component. Sometimes, the primary part will travel through a sequence of stations were various operations are performed, including the addition of other parts. However, for many processes the primary part will not move at all. An example of this is shown below where the operator manually loads/ unloads the primary part into a fixture where sequences of operations are performed on the part. In these types of processes, the "flow" is stationary.
Diagram D: Example of Process I/O where the part does not move.

There are at least three general areas that should be addressed on most Process I/O diagrams: Functions, operator interfaces, and general safety issues.

1.1 Functions: The example Process I/O diagram (shown above in Diagram D) forms a rivet in the part. Once the part and the raw rivet have been placed into the machine, the operator starts the process (start switch not shown). The first step is to clamp the part down by activating SV7. When the clamp is down, sensor S7 will signal the PLC for the next step. The second step is for Stepping Motor 2 (M2) to begin to move the slide towards the right to by pulsing Y2, with Y3 held on. The number of pulses will determine the number of steps to a defined position. The third step is to turn on the rivet head (M0) and to activate Solenoid Valve SV1. The head will come down and form the rivet. When the SV1 Cylinder reaches the S2 position, the controller will dwell for a predetermined length of time. At that point SV1 is deactivated and SV4 will raise the "SV1" Cylinder until S1 detects that the cylinder is at the top or "home" position. At that point a series of reverse order steps will be programmed until the
process is complete.

There are a number of items that should be noted. Certainly a much more detailed description could be written for this process but even this short explanation is fairly effective with the help of the Process I/O diagram for describing the process.

There are four basic "functions": Raising and lowering the Rivet head (SV1). The Rivet Motor (M0). The Clamp (SV7). And the Anvil Adjustment (M2). One of the first things that should be considered is to illustrate the "home" positions of each of the functions. It is good practice to illustrate all of the functions in their "home" or starting position on the Process I/O diagram. SV1 is shown to be retracted and should be detected by S1. M0 does not have a home position. SV7 is shown to be extended and is detected by S6. Systematically working through the functions of the diagram, it becomes obvious that M2 does not have a "home" position or sensor. In this case the Process I/O diagram is helpful in identifying the omission which should be added to the design. Also, since most lead screw applications require end of limit travel switches, this too is an omission that the diagram is helpful for pointing out early in the design phase of the project.

The key to developing these diagrams is to systematically work through all of the various "functions" by visualizing how the machine process should function, starting from their "home" positions.

Most functions, such as the four shown in Diagram D can be referred to by their primary output designation. Such as SV1, M0, SV7, and M2. Some functions may be controlled by more than one output, as is the case with SV1. For this function SV1 lowers the Rivet Head (extending SV1) and SV4 raises the Rivet Head (retracting the cylinder). While the function includes two outputs, SV1 and SV4, for simplicity, the function can be referred to as only SV1. Whatever designation is chosen, it is important to use it consistently throughout the documentation.

By definition, the "home" position is when there is no power to a device. Sometimes this is referred to as "on the shelf condition". In many situations, the result of the output is obvious, such as the case of SV7. When SV7 is not energized, the diagram shows the cylinder to be extended, or its home position. This means that when SV7 is energized the natural conclusion is that the cylinder will retract. It is highly recommended that the "home" position of all functions be illustrated on Process I/O
diagrams.

In the case of SV1, there is a dual coil solenoid valve which is controlling the direction of the cylinder. For situation where more than one output controls a function, it is necessary to add small arrows (as shown) and in the case of M2, one word notes are needed/ helpful. For functions where multiple outputs are needed, it may be necessary for the program to sequence through a series of steps to force the machine into all of the home positions via a "safe" sequence of steps to avoid mechanical crashes. In this case, possibly because of gravity, upon startup, SV4 should be activated until S1 is detected, just to verify that the machine starts out in the proper condition. The design engineer needs to evaluate every function for the design of the startup sequence.

(Note: Dual acting solenoid valves have the advantage/disadvantage of remaining in their last commanded position. In this case, once SV1 is "pulsed" the cylinder will extend, even if the electrical signal has been removed. If SV4 is "pulsed" the cylinder will retract. An example where dual acting control valves are very helpful is in situations such as a pneumatic gripper. The value of the dual acting solenoid valve is that the gripper will maintain its grip during an E-Stop (to be discussed later). If a single solenoid valve were used, the gripper would always drop the part upon an E-Stop event or when pneumatic pressures is removed.

In Diagram D (above) a simple box is used for all sensors. More complex symbols could be developed to distinguish between various types of sensors. The position of the sensor on the diagram in its relation to the device that is being detected is what is important. In the above example S1 signals that SV1 is retracted. S2 signals that SV1 is extended, and S3 signals that the cylinder has "over traveled", possibly indicating that there was a problem with the rivet process.

Many times the purpose of sensors on Process I/O diagrams is obvious by their location on the diagrams. This may seem trivial but for programming, startup and troubleshooting this is valuable information. As an example, if the step of the sequence of the process is to clamp the part (SV7) and the machine stops during "normal" operation, the diagram is very helpful. The diagram indicates that the first thing to be checked is to see if cylinder SV7 is actually extended or retracted. If it is still extended then SV7 can be verified to be energized or not. If energized, then the wiring, valve, and plumbing should be checked. If the cylinder is retracted, then S7 should be
evaluated. There could be a wiring problem or the sensor could be out of adjustment or defective. If the signal is reaching the PLC (as would be indicated by the Input LED on most PLC's) then there is probably an issue with the program or possibly the PLC is defective. Where this really becomes valuable is during the initial start up of a system because the failure of a function to sequence through a series of steps can be the result of a wide verity of interactive causes. As the complexity and size of a system increases the possibilities of what may need to be corrected dramatically increases. Therefore, while this sequence of troubleshooting may seem trivial, without a Process I/O diagram, startup times can be considerably longer.

For this small project shown, a Process I/O diagram may not seem needed. However, as time progresses, minor details can be lost or forgotten. Also, as projects are passed along and different personnel are involved, these diagrams become absolutely invaluable. For starting up a new piece of equipment or process, Process I/O diagrams should be used to systematically working through each of the functions. It is usually helpful to highlight each function in yellow as they are proven to be operating correctly.

Note: For complex sequences, it is sometimes valuable to write code so that the sequence of operations can be "single" stepped. Process I/O diagrams are also very helpful for these applications since it is obvious which inputs and outputs should be "on" during every step.

1.1.1 Many functions produce relatively little or no movement. Examples may be heating, drying, squeezing, etc. However, a major category of functions is where there is motion. Probably the two most common means of creating movement is through various pneumatic (or other fluids) and motors.

An important issue with motion types of functions is that when various functions are physically connected together it is important to illustrate this on the Process I/O Diagram. An example is shown in Diagram D (above) where cylinder SV1 physically moves the Rivet Head, M0. Often times a number of functions will be attached together. Grounding symbols can be used for clarity if desired.

1.2 A second major category that needs to be illustrated on Process I/O diagrams are Operator Interfaces. Operator interfaces are best represented on the Process I/O diagram by miniature "pictures" of the various operator control
Diagram E: Sample Process I/O Operator Interface.

These operator interface illustrations do not need to include a tremendous amount of detail. There are a few items that are typically helpful: Lights, symbols for various types of switches; symbols for misc. components; a name plate for each device, which should represent how the final panel will appear; and the device number.

Appropriate name plates will clearly "link" various operator interface devices and their related functions. Therefore, defining effective label descriptions for every device is very important. Many times it is helpful to physically "group" a number of operator devices, such as switches, lights, displays with related functions together under "header" labels. Examples are, "Heat Zone 1", "Heat Zone 2", etc. In the case where there are heat zones, it would be common to see items such as the temperature display, "Manual On-Off" switches, etc. for each of the zones. If the operator interface layout and labeling is designed properly, the interface will be clear and intuitive. Developing the operator interface, early in the design of a system (ie. during the development of the Process I/O Diagram) is very valuable towards defining and understanding how the system will ultimately operate.

Device "numbers" can use any unique number or designation. However, it is recommended that whenever possible that all devices numbers be related to their
associated PLC input and output numbers. An example of this would be a Program Reset button which if wired to Input #6, it could be designated as "PB6" ("PB" for Push Button and "6" for the PLC Input). It should be noted that the Power On button is designated as "PB B". "B" or some other generic designation is used because the Power On button is not associated with any specific PLC Input (thus a number as part of the designation could be confusing). An exception to this would be if the 24VDC power were wired into a PLC input. Then the input designation should become part of the label designation. (Note: There are a number of reasons why it would be useful for the PLC to be able to detect if the power has been cycled. One of the primary reasons is to prompt the PLC to cycle through a main startup or homing sequence.) This scheme of designating all devices with the Inputs and Outputs works very well and has been extremely valuable when also extended to wire numbers (which will be discussed further).

For larger systems the main operator control panel may reside on its own drawing sheet/s. However, if room provides it is helpful for smaller operator panels to be illustrated on or close to the associated equipment where various functions will be controlled by the operator.

Comment: There is a common temptation to add much more operator control than is needed. Over populated operator interfaces become very non-intuitive and even threatening for operators. It is important to identify the minimum controls that will be absolutely necessary. One approach that helps simplify control interfaces is to physically separate the operator controls from the controls that will be needed for maintenance and setup.

1.3 The third major category of devices that should be shown on Process I/O diagrams are Safety and Miscellaneous Interface devices. While Safety and misc. devices may not be associated with any particular function; these elements are extremely important, and should always be illustrated on the Process I/O diagram. One advantage of including Safety I/O during the development of the these diagrams is that important safety features can be considered sooner, allowing for smoother integration into control systems.
Diagram F: This project included a rotary table which progressively moved parts to the next index position. At each of the positions the next operation is performed by the related function/s. The associated equipment for each station is illustrated. Functionally, each of these stations effectively has its own "machine" which performs a specific task. Stations #2 and #3 allowed the operator to load/unload the "base" part.

Note: In sample Diagram F above, the Y27 Counter records the number of parts processed (designated by "A" below). Air pressure is often a critical process variable so it is good practice to incorporate a minimum Air Pressure sensor, as is illustrated as X7 in the diagram (designated as "B" below).

An interesting item to note in this diagram is the two light curtains (indicated by the "D" and "E"). There was a requirement to maximize the operator efficiency so the Start Curtain was incorporated, X0. This curtain detects when the operator places a part onto the rotary table. Then as soon as the operator removes their hands, the controller initiates the table to index. This approach removed the need for the operator to press a
separate start or index button. However, it is important to note that light curtain X0 was only used to start the index and was not a safety rated device. The X1 light curtain ("D" above) was independent and totally dedicated to the safety system.

The functions of the two curtains must not be confused with each other. When Safety Curtain "D" is interrupted, it is equivalent to an E-Stop event which requires a manual E-Stop reset. Therefore, one curtain could not be used for both functions.

Because safety devices are often not related to a specific portion of a machine, it is common for their designation on diagrams to be "floating" (such as devices "A", "B" and "C" above). Because of the lack of association with any specific mechanical function, it is usually helpful to include a single word or note to help describe "floating" elements.

1.3.1 A very important aspect of every Control System is the Emergency Stop Circuit (E-Stop System).

Every system has its own unique E-Stop safety issues. Therefore the design engineer must pay close attention and anticipate potential electrical and mechanical dangers.

**The activation of the E-Stop system may not remove all "energy" however; all motion must come to a stop and be prevented from restarting until the E-Stop is "reset".**

There are a number of forms (or types) of E-Stop devices. Each form is designed to meet various applications as well as appropriate codes and standards. The size, the color and a number of other features are defined by code, with the intent that they will be easy to identify during an emergency situation. Standard or non-safety rated buttons and devices should only ever be used with Category B Safety Systems (to be described later).

One feature of two position E-Stop buttons is that they remain in either the up or the down positions. By having E-Stop buttons to remain in the down (or Stop) position this allows the operator to have "local" control, thus preventing other personnel from resetting the E-Stop event back at the
main panel. This means that the E-Stop system should be designed so that all individual E-Stop buttons must be "cleared" (or manually changed to their up or ready positions) before the system is allowed to be reset.

One of the challenges of some systems is that as the number of E-Stop buttons and devices increases there may be times when the E-Stop system will not reset. By design, all E-Stop buttons should be individually reset or placed in the "up" position before the E-Stop system can be reset. Since it is difficult to detect if an E-Stop button is in the up or down position, it can become tedious to find which E-Stop device needs to be reset. One solution that helps eliminate the frustration of hunting down the "blocking" E-Stop button is the use of "illuminated" E-Stop buttons. The button can then be wired to indicate if each E-Stop button is in the up or down position. Then before attempting to reset the E-Stop system, it is much easier to locate which button/s needs to be manually reset.

1.3.2 Besides actual "buttons", there are a number of other devices that fall under the E-Stop category. It must be remembered that all components designed into a safety system must be properly rated and labeled by the manufacturer. The advantage of using properly rated devices is that the manufacturers are basically guaranteeing that the devices meet the appropriate codes for E-Stop systems. Regardless of the "type" of safety devices, they should always be wired directly into the safety system, thus avoiding electronics and program logic.

One example of an alternate type of safety device is a Safety Cable Switch. These switches are usually mounted on one end of production lines, such as conveyor so that a cable that is stretched along the front can be activated from anywhere along the line. Similar to all safety devices a number of codes need to be applied. Safety Cable Switch manufacturers usually provide good application information. Catalogue specifications should always be followed but most switches seem to specify maximum lengths of 75 feet cables.

A unique feature of Safety Cable Switches is that they are designed to
detect if the cable has been "pulled" or if the cable is too loose, or broken. It is recommended that a Cable Safety Switch be selected that incorporates a cable tension gage that is built into the switch. Without these gages, adjusting the correct tension can be tedious.

1.3.3 Another category of safety switches is for gates and doors. An example of this in Diagram E is the DS2 safety switch. These doors are typically used for operator functions during setup or to clear jams. These Safety Interlock devices should be part of the E-Stop system and therefore the E-Stop system will require a "reset" after all doors have been properly closed.

In cases where frequent access is not expected, and the need is limited to appropriately trained personnel, access panels do not necessarily need a safety interlock device. Such access panels require a "tool" to be opened. However, regardless of code, if the hazardous exposure is great enough, the design engineer may deem it necessary to specify Safety Interlocks. In extreme cases, automatic door locks which prevent doors from being opened until an E-Stop event has been initiated may be appropriate.

In the case of physically large systems, sometimes a fence/s is built around areas with gates/s to provide safe zones while still allowing personnel to have unrestricted access to the equipment after an E-Stop event has been initiated. To prevent personnel from entering danger zones, all access gates must be equipped with appropriate safety switches. There are a number of codes regarding safety fences and gates that should always be followed. Again, manufacturers of these safety devices are usually quite helpful for providing information on how to properly install their products.

Note: Safety Fences and Gates, incorporated into E-Stop systems should never be used where lockout and tag out procedures should be used.

1.3.4 There are several technologies that are available for panels and gates:
light beams, magnetic sensors, and mechanically "keyed" limit type switches. Regardless of the type of technology, all of them incorporate some type of anti-tamper mechanism. There is usually a fixed component that is attached to a frame and a matching component that is attached to the door or gate. The intent of the anti-tamper mechanisms is to prevent personnel from opening a door or gate, inserting a dummy device and then restarting the process with the door or gate open. Regardless of these anti-tamper mechanisms, management should always take steps to prevent employees from bypassing safety systems.

Light curtains consist of a series of beams to form a "curtain". Each beam is pulsed at particular frequencies which prevent one light beam from being reflected or to confuse a neighboring light beam channel. With a specific frequency only being recognized by the various channels, it is obvious that a flash light or some other light source will not work to bypass these types of safety devices.

Magnetic sensors use a series of magnets which are arranged so that the North and South poles create a unique combination that can only be detected by the mating sensor. Even with only a few magnets there is a lower probability of finding a spare "key" with the correct combination, thus making it difficult for personnel to defeat the sensor by the use of a substitute part.

Probably the most commonly found anti-defeat technology is the mechanical limit switch. These approaches use various types of mechanical "keys". Only the correct "key" will fit into a specific "lock" (switch) thus making it difficult to be bypassed.

1.3.5 Light Curtains consist of one or more individual "beams" that form a virtual grating across the opening. A major area of concern is how far apart or how big the gaps are between the beams. The actual spacing is specified by code and implemented by the manufacturer. The design engineer needs to be particularly concerned with the size of the inactive space above and below light curtain installations. Physical guards may be
appropriate for areas above and below light curtains.

Single beam sensors are sometimes useful to protect operators from reaching through a small opening. While any number of sensors could be used for this application, only appropriately rated safety components should ever be used.

Another concern with light curtains is that personnel can quickly thrust their hand through the light curtains before the motion can be stopped. There are formulas for calculating the distance that light curtains should be installed away from danger points. Again, manufacturers can be very helpful to help design light curtain installations that meet applicable codes and standards.

1.3.6 Safety Mats and area proximity detectors: Sometimes there are applications where it is necessary to verify that an operator is clear from a specific area before certain motions should be started.

One possible example is where an area is protected by a perimeter safety system, such as a fence and gate. However, it is still possible with such a system for personnel to remain inside of the fence, while someone else closes the door and resets the E-Stop event. If it were absolutely critical that no personnel ever remain inside of the safety perimeter, safety mats or area proximity detectors could be implemented so that it would be very difficult to "fool" both safety systems.

Safety Mats are basically floors mats which detects if someone is standing on the mat or not. They appear as a simple on/off switch to the control system. Mat shapes and sizes can be simple or complex. Safety mats are designed to be pressure sensitive so that the weight of personnel is detected while other objects may not, depending on the design of the mat. However, objects with the correct pounds per "foot area" may be falsely detected.

Safety Proximity Sensors detect if an object is present within the areas that the sensor covers. The results are similar to Safety Mats. Because
the sensors operate on a "line of sight" from the sensor, it is common for there to be obstacles within the zone, such as a frame member. To accommodate such applications, Safety Proximity sensors can be "programmed" to mask certain areas. However, wherever a zone is masked, the shadow of that zone will not be protected by the sensor.

1.3.7 One of the most common operator Safety Systems is the two-handed-no-tie-down system. This system is relatively simple because it consists of two separate switches that are permanently mounted far enough from the hazard area and far enough apart to force the operator to have both hands in safe location before the potentially hazardous motion is allowed to move.

There are a number of codes which dictate the mounting distances and other aspects of the operation of these safety systems.

A major requirement is that both switches must be activated within a short time period. This and other time requirements are designed to prevent operators from using objects to "fool" the safety system (such as taping one of the switches in the down position). Two-handed-no-tie-down systems incorporate a safety rated controller that demands that both switches are properly cycled together before the output is activated.

A potential nuisance with these systems is that if the operator does not activate both switches within the allotted time requirements, the safety system will not activate the output. For operators who are unfamiliar with these systems (such as engineers) the lack of response from two-handed-no-tie-down systems can appear that there is a malfunction.

It is very common for two-handed-no-tie-down systems to be incorporated into equipment with relatively high cycle rates (less than 10 seconds per cycle). The problem that is created with high cycle rate applications is that no matter how light of the force needed to activate the two switches, the high repetition rate tends to create ergonomic issues. A good solution to avoid these problems is the incorporation of optically activated "push" button switches. Optically activated switches require no force, only for the
operator to place one finger from each hand into the two optical beams.

Two-handed-no-tie-down systems require a safety controller that has specifically designed for this application which meets all of the timing requirements. While such controllers add some cost to systems, the safety features that are provided is usually well worth the relative minor additional costs.

2 Supply Power Selection:

The next step after completing the Process I/O diagram is to develop the wiring diagrams or wiring schematics.

Before the wiring can be designed, it is very important to understand and apply all appropriate codes.

2.1 Codes: Because of the massive volume of Codes that apply to the design of control systems, only a brief introduction is presented here. Therefore the reader is strongly encouraged to complete further study in these areas.

It is important to understand that codes are very valuable. Codes generally describe good engineering practices. More importantly, because a large percentage of codes are written in response to incidents that resulted in the loss of life and property, codes should be viewed as design criteria which others have paid high prices for.

However, as valuable as codes are, they should also be considered to be only minimum requirements. Because of the infinite possibility of equipment and processes, after all appropriate codes have been implemented; the design engineer should always carefully evaluate and address all potential safety issues.

The potential of developing new and unique processes does sometimes require designs that deviate from some existing code. How to secure waivers is a complex subject and is beyond this presentation. While there may be exceptions, the intent is to help the reader be aware of existing codes and their importance.
Most codes are updated on a yearly, every two year, or other schedule cycle. The latest version of codes should always be used.

Two important sources of codes are the National Fire Protection Agency (NFPA) and American National Standards Institute (ANSI).

2.1.1 NFPA is responsible for about 300 codes and standards. Below is only a short list that may be applicable for control system designs:

- NFPA 1, Fire Code- Fire safety for buildings.
- NFPA 70, National Electric Code-Electrical Installation.
- NFPA 79, Electrical Standard for Industrial Machinery

Specific attention should be given to NFPA 70 which is commonly referred to as the National Electric Code, or NEC. Another very important code that applies to control system design is NFPA 79. Because these two codes apply to most control systems, every controls design engineer should become thoroughly familiar with at least these two codes.

2.1.2 ANSI is responsible for codes that cover a wide range of applications. Below is a list of some standards that typically apply to control system designs:

- ANSI B11.1-1982 Mechanical Power Presses
- ANSI B11.2-1982 Hydraulic Power Presses
- ANSI B11.3-1982 Power Press Brakes
- ANSI B11.4-1983 Shears
- ANSI B11.5-1988 Iron Workers
- ANSI B11.6-1984 Lathes
- ANSI B11.7-1985 Cold Headers and Cold Formers
- ANSI B11.8-1983 Drilling, Milling, and Boring Machines
- ANSI B11.9-1975 Grinding Machines
- ANSI B11.10-1983 Metal Sawing Machines
### ANSI Standards for Machine Control Systems

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Electrical Standard for Industrial Machinery

ANSI/RIA R15.06-1986  
Industrial Robots and Robot Systems

ANSI Z8.1-1972  
Commercial Laundry & Dry-Cleaning Equipment

ANSI Z241.1-1989  
Foundry, Sand Prep., Molding, & Core-Making

ANSI Z241.2-1989  
Foundry, Melting & Pouring of Metals

ANSI Z241.3-1989  
Foundry, Cleaning & Finishing of Castings

ANSI Z245.1-1984  
Refuse Collecting & Compacting Equipment

ANSI Z245.3-1977/83  
Stability of Refuse Bins

ANSI Z245.5-1982  
Bailing Equipment

ANSI Z268.1-1082  
Metal Scrap Processing Equipment

2.1.3 While most codes are "national", it is very common for individual states, and even Cities to adopt additions requirements. Probably the most common instance is the requirement that Control Panels are wired and labeled by an independent testing laboratory. Underwriters Libratory (UL) is probably the most popular standard in most but not all States/ cities.

2.1.4 Most County and State inspectors will probably not inspect what is inside of control panels, but they will look for and depend on if a panel is built and labeled per UL or equivalent standards.

For a consumer product, such as a toaster, there is usually a fair amount of time and cost to obtain a UL listing. However, consumer products and industrial control panels labeling should not be confused. A UL 508 certification (Safety Standard for Industrial Control Equipment) allows a UL "licensed" electrical panel shop to assemble, wire and label industrial control panels. The cost and effort to obtain a UL 508 certification is relatively reasonable. The ultimate result of panels properly wired per UL 508 will be high quality panels which should meet most applicable codes and be accepted by most inspectors.

Therefore it is highly recommended that all control panel designs be specified to be wired and labeled per UL standards (or equivalent). Many States will not allow equipment with control panels to be installed without such labeling. However, not too many years ago, there were a fair
number of non-UL panel shops producing unlabeled control panels, which means that there is a fair amount of un-labeled existing equipment in industry. In the event that one of these non-labeled pieces of equipment needs to be updated (such as if it is re-installed, especially if in a different State) there are consulting firms which specialize in inspecting and labeling existing equipment. It should be expected that most of these inspections will result in additional costs to rewire and possibly replace some components, but the entire control systems usually will not need to be replaced and these costs are usually reasonable.

2.1.5 It is common for control panels to be designed in the States and then to be shipped to various foreign countries. Because there are a variety of foreign standards, the design engineer should always determine what the appropriate codes and standards will be required to allow the equipment to be passed through customs and ultimately installed. However, even if no foreign codes are required, all US codes should be followed as minimum standards.

2.2 Once the appropriate codes have been identified, the first step is to determine if a system should be single or three phase. This can be easily done by systematically working through the Process I/O diagram and tallying the total horsepower (hp) of the system/s.

Some loads will be in hp and others will be in Kilowatts (Kw). Kw can be converted to hp by using the ratio: 1.341 hp = 1 Kw.

Of course if any of the devices in a system are only available in three phase, the supply must be three phase. However, if three phase is not required by any of the devices, given a 480 VAC (Volts Alternating Current) system, single phase can be specified if the total load equivalent to 5 horsepower or less. If the available voltage is 240 VAC, a single phase system can supply about 3 horsepower. For a 120 VAC system only about 1 horsepower should be supplied. As the current requirements exceed these rules of thumb, the amp capacity (ampacity) of wire and the size of other components begin to be more expensive and three phase power sources should be considered.
Another major factor in choosing single or three phase is what is available in the facility where the project will be installed. Fortunately, most industrial areas are supplied with three phase. In cases where three phase is not available but required by the equipment, there are single phase to three phase converters. These converters are fairly expensive.

2.3 After determining if the power supply is single or three phase, the next step is to determine the incoming voltage. The typical standard voltages in industrial areas are: 120, 208, 240, 277, and 480. The available voltages should always be verified so that the design will match what is available.

Usually, the primary consideration for determining the supply voltage is what is already available in the facility. Sometimes there are good justifications for a different voltage, especially if the existing power transformers are close to their maximum output and a new transformer will need to be installed. However, there are advantages to maintain consistency throughout a facility, especially if there is the possibility that some pieces of equipment will be moved to different locations within a facility.

Many times the determining factor for choosing the supply voltage of a system is dictated by the requirements of major critical equipment modules or pieces of equipment, such as a laser or an x-ray module/machine.

Motors are usually available to operate at most of the standard voltages. Many motors have the capability to be rewired (in the junction box of the motor) to be able to operate at different voltages. As a result, motor requirements usually don't impact the voltage decision but there are instances when the available motors will dictate the incoming supply.

If the motor or critical module does not require a relatively large power source, special voltages can be obtained by incorporating a step up or step down transformer into the controls system itself.

2.3.1 Sometimes motor voltages do not exactly match the incoming power of a system. As an example, it is not uncommon for a 230 VAC rated motor to be powered within a 240 VAC system. In this case, the motor will draw slightly less than the rated current. In the situation that a 240 VAC rated
motor is supplied with 230 VAC, the current of the motor will be slightly higher and the motor will operate at a slightly higher temperature. Because the 10 volt difference is only about a 4%, the higher temperature that result from the higher operating current is usually not a problem.

Note: Regardless of how well component voltages match supply voltages, it is recommended that the current of all major loads, especially motors be verified and recorded as part of the commissioning process. This will help verify that motors will not overheat.

2.3.2 If a single phase system requires about 1 total hp or less (1.9 kw) a single 20 amp, 120 VAC circuit will probably be sufficient. (Note: 120 VAC is what is commonly available in "standard" wall receptacles within the US.) As a result of the very large quantities of components that are manufactured for 120 VAC systems, this supply voltage will always be the most cost effective.

2.3.3 It should be remembered that most standard electrical components have a 250 max voltage or a 600 voltage rating. All components must have a higher voltage rating than what the component will carry within systems. This means that for a 480 volt system, the components will usually all be rated for 600 volt. In cases where very large motors are involved, to minimize the current, wires sizes and transform requirements, higher than 600 volt supplies can usually be provided by utility companies. However, it should be expected that the components and installation costs will be relatively more expensive for these less commonly used components.

2.3.4 480 VAC supply power: The fundamental physics of most types of motors is that they will attempt to maintain their "basic" speed (RPM's). As the load increases, most types of motors will draw more current. Conversely, as the load is decreased, the motor current will be proportionally less. Thus, the actual motor current is representative of the hp required for the motor, not the actual size of the motor. As long as the motor hp rating is larger than the load hp required, under normal conditions, the motor will not overheat.
Conversely, if the voltage to a motor is increased the current will be proportionally smaller for the same load. Essentially, the energy in (amps x volts) is roughly constant per hp.

Therefore, if a motor operates on 480 VAC instead of 240 VAC, the current will be very close to half. Since wire size is related to the current and not the voltage, higher motor voltages result in less amps and smaller less expensive wire, and transformers. (Smaller wire means less copper and installation labor). Because of these lower costs, many electrical engineers who design facility power systems tend to specify 480 VAC systems.

2.3.5 Arc Flash Potential: Since higher voltages tend to increase the Arc Flash Potential, which requires more restrictive protective equipment for working within higher voltage environments, the potential installed cost savings of 480 and higher volt systems should be carefully evaluated. If the right conditions exist, a full body suit may be required, which could ultimately result in longer equipment down times when maintenance activities are required.

These are not absolute rules but Arc Flash potentials can generally be minimized by three general approaches: Proper fuse/ CB selection, designing for lower voltage supply systems, and installing supply power transformers with limited amp capabilities.

2.3.5.1 Fuses tend to be better devices for limiting Arc Flash potential because they can usually be sized to limit the time of the arc. If fuses or CB’s are intended to minimize the Arc Flash Potential, a fair understanding of the science is needed for proper selection. Therefore, these device selections should always be reviewed by appropriate resources.

Some falsely expect that through careful selection of fuses and CB’s that the Arc Flash Potential can be minimized and predicted by the control panel manufacturer or equipment supplier. However, since the Arc Flash Potential is significantly influenced by the potential of the supply current and voltage, the Arc Flash Potential must be determined with respect to the installed voltage supply that feeds the equipment.
Therefore, appropriate resources should be contacted to determine the level to Arc Flash which will dictate the safety equipment that will be required to safely work on these systems.

2.3.5.2 Lower Arc Flash Potential can usually be obtained by the installation of lower voltage power transformers. While additional transformers may be expensive, given the high cost of down time for some processes, decreasing the need of awkward safety equipment may result in net savings.

2.3.5.3 The higher the current capability of power transformers, the higher the Arc Flash Potential will be. Therefore, a lower voltage power transformer with a considerably higher amp capacity may result in increased Arc Flash Potentials. New power transformer capabilities should be carefully evaluated. In general a number of smaller power transformers in a facility will result in lower overall Arc Flash Potentials than a single large power transformer.

2.3.6 Another consideration for not using 480 VAC is that a wide variety of electrical devices are rated for only 250 VAC and below. 480 VAC systems require all components, including replacement fuses to be rated for 600 VAC. Since 600 VAC rated fuses are designed so that they cannot be interchanged with the 250 VAC rated fuses. If a system is designed for 480VAC, care must be taken to have an adequate supply of 600VAC rated replacement components.

Bigger is not always better. Generally speaking, the lowest supply voltage that provides a reasonable margin of power for a system should usually be considered.

Note: If a system is powered by 480 VAC, an approach that will minimize Arc Flash and other high voltage issues is to separate the wiring between "control" design cabinet/s and "power" cabinet/s. Code does not require this but if the maximum voltage in the control cabinet/s (where considerably more access will be required) is kept at 120 VAC or below and the amp supply is kept at a minimum, the Arc Flash Potential will be much safer than for the higher voltage supply cabinet. However, it should be remembered that the 120 VAC control cabinet/s will still contain "high" voltage and should be respected as such.
2.4 Once the supply voltage has been selected, the next step is to refine the current (Amps) requirements for a system. All loads will ultimately need to be converted to the total amps required.

When designing requirements for a heater, processes will generally require a total Kw of heat. However, when designing control systems, it is the amps per phase that is important for determining wire size and circuit protection. In a 3 phase system, because the current in each of the three phases are out of phase with each other, the current for each of the three phases will not be equivalent to 3 times the current of a single phase heater. I.e. the current per phase for a 3 phase 30Kw heater will not be the same for a 30Kw single phase heater. If the amps per phase are the same for both a 3 phase heater and a single phase heater, there will be a difference between the BTU outputs of these two heaters. Furthermore, there is a variety of 3 phase systems. For the sake of simplicity, when designing for heater loads, the amps per phase must be determined and one of the best sources is the heater manufacturer specifications.

Generally, to convert Kilowatts to Amps, the amps per phase can be determined by dividing the Kw load by the supply voltage and multiplying by 1000. Example: A 10Kw load supplied by 240 VAC would be equal to approximately 42 amps (10 / 240 x 1000 = 41.7).

In the case of motors, because horsepower defines energy, the current for a 5 hp single phase motor will not be equal to 3 times the current of a 5 hp three phase motor. As an example, at 230 VAC, a 5 hp single phase motor will draw about 28 full load amps while a 5 hp three phase motor will draw 15.2 full load amps per phase.

For single phase, the relationship between Kw and hp is: 1.341 hp = 1 Kw.

To determine the amps from hp, one of the easiest methods is to use a "paper calculator". These charts/calculators will take into consideration if the motors are single or three phase, the operating voltage and sometimes even the power factor. The "paper" calculators have been available from many motor supply companies. However, similar tools can easily be found on the internet (searching for "horsepower to amps calculator" will usually provide good results). Power Factor is not usually a significant parameter, especially with systems with smaller hp loads. A good Power Factor to start with is 85%.
The above methods are good to determine the current during the design phase of project. Once motors part numbers have been identified, the full load current should be available in the catalog literature and should also be stamped on the motor nameplates. Once all of the specific motors have been selected, the total current should be verified.

The total current for a system is usually defined to be the sum of all of the Kw loads and all of the motor loads, plus 25% of the largest motor load that will be operated at the same time. If the current value can be comfortably supplied through one of the standard CB sizes, then the rating of the CB can usually be used. However, if the expected operating current is close to a standard CB size, and there is not a comfortable margin, then the next larger CB size should be selected.

Note: There are some exceptions when addressing systems with multiple motors, so for those cases codes, especially the NEC should be reviewed and applied.

When designing a new system, especially with larger power requirements, it is important to determine if the power is available within the facility. Often times it is necessary to have a power survey completed. Power survey results will measure the maximum total current that is consumed by a facility over a specified time period (usually a few weeks to a month). If the maximum power usage plus the expected power of a new system is close to the maximum available power, then additional power transformers and sometimes even additional services into the facility may need to be installed. Permit agencies will usually require that power surveys and any resulting new transformers installation designs be provided by an appropriately licensed engineer.

Summary:

The process that has been described to develop Control Systems is based around the development of the Process I/O diagrams. This diagram becomes a roadmap for determining to total amount of power that will be needed by the system. The number of phases, the supply voltage, and the total current all need to be determined to specify the incoming power that will be needed by the new systems.

With the Process I/O diagram and the incoming power requirements defined, there are a number of steps required to complete the design of a control system. These steps are
described in Part 2 of this course.