Chapter 1
Basic Characteristics of Control Systems and their Representation
Process and Instrument Diagrams

We need ways to describe process control systems. We will learn several ways in this course. The oldest way is the Process and Instrument Diagram (P&I diagram). You have probably seen these in your summer work. Formal diagrams are developed by mechanical engineers and contain enough information to purchase the instruments. Process engineers use less formal ones as part of the process flow diagram. We will use some intermediate form. You need to be able to understand them and to develop ones of your own so you can get the help of mechanical and instrument engineers to implement your control ideas.

In this course we will be dealing with "advanced controls", those controls that try to run the unit in the way an experienced operator does. P&I diagrams are really designed to handle low level controls such as flow controls. Figure 1 is the P&I diagram for a flow controller:

![Figure 1. P&I diagram of a flow controller on-line feeding a pressure vessel.](image)

The process piping is shown with a control valve. The measurement of flow is shown with a "bubble" with a thin line to the process at the point where the measurement is made. The measurement is made by a "sensor" or "transmitter"; steam flow is measured using an orifice plate and a sensor that measures the pressure difference across the plate. The sensor converts the differential pressure information into an electrical signal proportional to the flow. The electrical signal is in the range 0 to 20 ma. This signal is sent to the controller, shown as a second bubble. The signal line is shown as a dashed line. The controller compares the signal from the sensor with a reference signal that the operator has set -- called the setpoint. It sends a signal out to the valve to make any necessary adjustment to cause the actual flow to match the setpoint.

Control valves are shown with a valve stem and a half circle which indicates the valve motor. Valve motors are usually pneumatic actuators so there is a part that converts the electrical signal into an air signal. The air signal is in the range 3 to 15 psig.
In modern plants, the controller may be part of a "DCS", Digital Control System. Sometimes this is shown on the P&I diagram by putting a square around the bubble representing the controller. The sensor or transmitter and the control valve are the same whether or not there is a DCS involved. The main effect is that the operator uses a computer keyboard and screen to enter his setpoint rather than a knob on a separate controller.

Notice the notation used inside the bubbles. FT means flow transmitter. FC means flow controller. In a more elaborate diagram with many flow transmitters and controllers numbers would be included in the individual bubbles to permit specific flow controllers to be discussed. In a large diagram the numbers may be coded in ways that identify the portion of the plant involved. We only need to be aware of such rules so we can discuss controls intelligently with plant people.

The alphabetic notation inside the bubbles permits a full range of different sensors and controllers to be discussed such as PT and PC for pressure controls, TT and TC for temperature controls, LT and LC for level controls.

P&I diagrams can also be used to indicate advanced controllers. Often, however, such controllers involve more than one sensor in the control decision. No one has ever developed a standard way to represent things like that on a P&I. A simplified basis weight controller can be used to develop the idea.

![Figure 2. P & I Diagram of a Basis Weight Controller](image)

This is actually a very crude description, but it serves a key purpose: it is probably understandable to people who are familiar with process controls and paper machines. The paper machine itself is inside the "black box". We will look inside there later. The line coming in on the left is the heavy stock flow to the machine. The line going out on the right is the paper web itself, say just before it is reeled up. The stock flow line has a flow control loop. Note that with stock flow, we are talking about a more expensive sensor than that used in steam because it is not feasible to measure stock with an orifice plate. Instead, we use a "magnetic flow meter" which applies a magnetic field to the fluid and measures a voltage at right angles to the field. The voltage is proportional to the flow.
The controller is the same in any case, since the more expensive mag flow meter still comes out with a 4 to 20 ma signal proportional to the flow. The valve may have some special properties but it still accepts the 4-20 ma signal from the DCS or controller.

Now, the diagram shows much more than the flow controller. Specifically, a sensor is shown on the web line which is measuring the basis weight of the web. More about that later. For now, follow the dashed line from the basis weight sensor to the basis weight controller, and then from that controller to the flow controller. This represents a classic "advanced control" idea called "cascade control". The idea is that the setpoint of the flow controller, that is the flow desired in the stock flow line, is set, not by the operator, but by the basis weight controller. It is comparing the actual basis weight with the basis weight setpoint entered by the operator and generating an output which is the stock flow it thinks will just match the two up.

On the P&I diagram, the flow transmitter and the basis weight transmitter look pretty similar. There is one very big difference that does not come out: cost. A basis weight sensor probably costs $500,000 or more. A flow transmitter costs from $2000 to $30,000 at the outside. I usually distinguish between "conventional sensors" and "special sensors". Flow sensors are usually "conventional"; basis weight sensors are always "special". A special sensor costs a lot and often doesn't work very well in the sense that it doesn't measure the thing it is trying for very well. Basis weight sensors are an exception in the sense that they do a very good job of measuring basis weight -- but they sure are expensive, so we keep them in the "special" category.

One reason basis weight sensors are expensive is that they are capable of traversing across the full width of the paper web and reading out the weight per unit area continuously as they are traversing. We are able to distinguish two aspects of the web: the trend of basis weight with time as the average across the web; the "cross direction variations". Basis weight control over the average weight became common place in the industry during the '70s. Cross direction control is more complex and the number of machines using it is still growing after an increase in the rate of applications began in the early 80's. Even before automatic cross direction control became available, the basis weight sensor was used by operators to guide their efforts to level the web in the cross direction.

CHARACTERISTICS OF CONTROL PROBLEMS

Basis weight control provides us with a clear example to explore some key ideas of control. We have already used it to illustrate "cascade control". More fundamentally, though, there are two critical requirements that must be present for there to be an advanced "control problem". First, there must be a "specification" to be met. Basis weight is the primary specification of a paper product. Basis weight is the weight per unit area of the paper. It is measured as grams per square meter internationally and as pounds per
ream commonly in the US. Papers are produced in a very wide range of basis weights, from say 10 pounds per 2800 square foot ream for tissue to 400 pounds per thousand square feet for paper board. A common book paper is 50 pounds per ream. If you buy it from a paper manufacturer, and go ahead and test the paper, you will typically find that individual samples come out in the range 48 to 52 pounds per ream, and the standard deviation of a large number of samples is less than one pound per ream.

This reflects the existence of two things: first, a recognized specification on acceptable basis weight for 50 pound book paper; second, the existence of processing equipment capable of meeting this specification. A specification may be presented mathematically as:

$$48 < BW < 52$$

using inequalities to give the acceptance range.

But why do we find variations at all? Apparently, the apparatus that makes paper is subject to such variations. Sometimes we are able to identify key causes of deviation from the midpoint of specifications. Basis weight variations are primarily due to variations in the consistency of the heavy stock flow. To fully understand this we would need to look into the method by which we attempt to set the consistency, or fraction by weight of fiber in a stock stream. For the present, it is sufficient to grasp the notion that variations in the consistency means variation in the amount of fiber available to spread out over the web, and hence variations in the basis weight. Our goal here is to bring home the meaning of the term "disturbance" which is how control engineers generically describe process variations that tend to cause the measured property to deviate from the desired value.

The essence of a control problem is as follows. We have a measurable property of the product of a process which must meet a specification. There exist disturbances which cause the property to vary away from the nominal value and potentially outside the specification range. There exists a flow or other adjustment on the process which can be manipulated by a controller and which is capable of restoring the process property to the desired value. The following table applies this definition to the basis weight control:

<table>
<thead>
<tr>
<th>measured property</th>
<th>basis weight (wt per unit area)</th>
</tr>
</thead>
<tbody>
<tr>
<td>specification</td>
<td>$48 &lt; BW &lt; 50$ or $50 \pm 2$</td>
</tr>
<tr>
<td>disturbance</td>
<td>consistency of heavy stock</td>
</tr>
<tr>
<td>manipulated variable</td>
<td>flow rate of heavy stock</td>
</tr>
</tbody>
</table>

There is an implied characteristic here which control engineers call "causality". In the example, there must be a causal link between heavy stock flow and basis weight. Increasing the stock flow must reliably imply an increase in basis weight of the paper. In the design of advanced control systems, some effort may be required to find a manipulated variable with the correct causal link to the property of interest. Of course, in
any operating process subject to disturbances, the process operators can be looked upon as controllers of the process. We get ideas about suitable manipulated variables by observing how they attempt to bring the process back to the desired value when it is off spec.

What is the causal principle at work when we increase heavy stock flow rate so as to raise basis weight? Of course, it is the fundamental physical law known as the conservation of mass. In the case of basis weight control, it is feasible to attempt to obtain an algebraic representation of the causal link between stock flow and basis weight by direct application of the conservation of mass. We will do this soon. More generally, though, the causal link might involve heat transfer, mass transfer, fluid flow, thermodynamic, chemical reaction stoichiometric, or chemical reaction rate principles.

What, for example, is the basis for the implied causal link in a digester control system that measures and attempts to control kappa number of the pulp by manipulating liquor to wood ratio? In such cases we may only use the theory to establish the belief that the causal link is present. If we wish to quantify it we will typically have recourse to experimentation; often, directly on the process. Control engineers use a special approach to the experimental tests and the treatment of the data, both of which will be well covered in this course.

**REPRESENTING CAUSALITY**

Control engineers use diagrams to represent the causal links in a process. Such diagrams will be found in articles on control and in proposals from control system vendors to paper mills. Some forms of the diagrams are well standardized; others follow only general guidelines and the details must be explained in supplementary notes by the engineer who developed them. I use an approach called a functional diagram to present process behavior and control systems in overview. The functional representation of our basis weight controller is presented below:

Actually, this diagram consists of two separate parts which are joined to form the version above. First and foremost, there is a functional representation of the process as shown in Figure 4:
This representation expresses one and only one aspect of papermaking. It reminds us that basis weight is a "response" of the process. Process responses are shown as arrows or lines leaving the "process block" on the right. It further reminds us that heavy stock flow is the manipulated variable that we use to adjust basis weight. Manipulated variables are shown as lines or arrows entering the process block from the left. Finally, it reminds us that variations in consistency of heavy stock "disturb" the basis weight of the paper. Disturbances are shown entering the process block from the top.

The process block represents our belief that the paper machine process converts the "inputs", stock flow and consistency, into the "output", basis weight. The reason I call it a functional diagram is that it expresses graphically the same idea as the following mathematical formula:

\[ BW = f( FS, CS) \]

where BW is the basis weight,
- FS is the stock flow,
- CS is the stock consistency,
- \( f \) is the functional notation of calculus.

In this case it will be possible for us to subsequently derive the function from first principles. Generally, though, we are merely asserting our faith that such a function exists and, perhaps, our belief that we could experimentally determine the function in a limited range by experimentation on the process.

The second block in our initial functional diagram is the controller block. It is shown on the left of the process block described above and is presented in isolation below:

Figure 5. Functional Diagram of a Basis Weight Controller
From the relative positions of things we can imply that stock flow is the "response" of the controller block and the "inputs", basis weight setpoint and measured basis weight somehow determine the response. We can infer the existence of an equivalent mathematical relationship:

$$FS = g(\text{BWSP}, \text{BW})$$

where BWSP is the basis weight setpoint and g is some function. Actually, the characteristics of the functions used is an important topic in this course, but we aren't ready for it yet.

Having seen the two components of the original functional diagram, go back to it and see how the two parts were joined to represent the whole. We now know how to represent the paper machine as a functional block as far as basis weight response is concerned. Actually, that part of the diagram is exactly the functional representation of a paper machine without a basis weight controller. That implies that it would be possible to make a single block representation of a paper machine with a basis weight controller in place. To make such a representation, which is quite a useful thing to do, we must decide what the response is, what the input is, what the disturbance is. Then we draw a block, put the response as an arrow on the right, the input as an arrow on the left, and the disturbance as an arrow entering from the top.

The diagram below is the representation of a paper machine with a basis weight controller. Note, our goal here is to show the process behavior, not the details of the implementation as in our original functional diagram. Note also that the input in this case is much more abstract a notion than the stock flow input in the diagram of the process without control. This underscores that these diagrams are not process flow diagrams. They are "information flow" diagrams. The basis weight setpoint "information" is the real input to the controlled process. As it happens, the disturbance representation is identical in both situations. However, in both cases the diagram is saying that information about the disturbance yields information about the basis weight.

![Functional Diagram of Papermachine with imbedded Basis Weight Controller](image-url)

Figure 6. Functional Diagram of Papermachine with imbedded Basis Weight Controller
SAMPLE ASSIGNMENT: MOISTURE CONTROL

Moisture is a key property of paper. Paper is dried to a desired moisture by rolling it over steam heated dryer drums. The pressure of the steam in the drums can be manipulated with a valve between the drums and the plant steam header. Typically, the valve is set by a pressure controller. The setpoint of the pressure controller determines the temperature in the drum and thus the heat applied to the paper. The moisture of paper at the reel of the machine can be continuously measured with a "special sensor" called a moisture gauge. Besides the steam pressure, the moisture out of the dryer depends critically on the moisture out of the press section of the paper machine which itself can be shown to depend on the freeness of the incoming stock.

Develop the ideas above into a description of moisture control on a paper machine. Include a P&I diagram, a functional diagram of a paper machine dryer, a paper machine controller, both in one diagram, and an overview diagram of a machine with the controller in place. Describe the specifications, disturbances, and causality involved in this situation.