Chapter 3

Sensors and Actuators

During the design process the motion requirements of the problem are transformed by the mechanism into a set of requirements for the electromechanical devices (sensors and actuators). In designing a system we must choose devices whose characteristics meet the requirements presented at their ports on the mechanism.

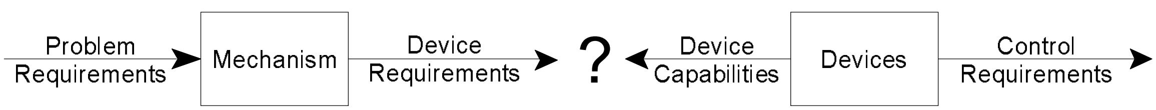


Figure 3.1: Device Requirements vs. Device Capabilities

For example if an elevator is to serve three floors with a load capacity of 1000 pounds, the motion requirements at the load might be to lift 1000 pounds through a distance of 20 feet with a maximum velocity of 5 feet/second. Using a 1 ft diameter windlass and a 50:1 gearbox this translates into a requirement for the motor of 100 ft-lb of torque at 4800 rpm and requires either a linear sensor at the car with a range of 20 ft or an angle sensor on the windlass with a range of 2300°.

3.1 Ideal vs. Real Devices

3.1.1 What we Want: Ideal Devices

The Ideal Sensor. A sensor's task is to convert a mechanical quantity to an electrical signal and present it to the controller. The ideal sensor would be a box with a mechanical input on one end and an electrical output on the other for which $e_{out} = Km_{in}$, where m_{in}

is the mechanical input and e_{out} is the electrical output. For many sensors we can achieve behavior very close to this over some limited range of input.

The Ideal Actuator. While we might like to have a box for which $m_{out} = Ke_{in}$, physics makes this difficult if m_{out} is a position or velocity. If we had a box for which $x_{out} = v_{in}$, with x in meters and v in volts, then if we set $v_{in} = u(t)$ (where $u(t)$ is the unit step function), we can't have $x_{out} = u(t)$ without exceeding the speed of light. Or, if we had a motor for which $\omega_{out} = Kv_{in}$, the maximum power we could deliver would limit its rate of acceleration in response to a step input, unless $J_{load} = 0$.

The Ideal Realizable Actuator. The mechanical quantity which we can have directly responsive to an electrical signal is force (or torque). I.e we can have a box for which $F_{out}(t) = f(e_{in}(t))$, for any $e_{in}(t)$ regardless of the load. In some cases this relationship is linear, i.e. $F_{out} = Ke_{in}$.

3.1.2 What we can Build: Real Devices

Real Sensors. A sensor needs to extract *information* from the mechanical system, and this can often be done without removing a significant amount of *energy* from it. This means that the influence of the sensor on the existing mechanical dynamics is often negligible, and we can regard its output as instantaneously following the component to which it is attached.

No real device can have $e_{out} = Km_{in}$ over an unlimited range, due to either electrical or mechanical limits. In some cases the limited range of the basic sensor can be extended to make it essentially unlimited. For example, a one foot ruler can be used to measure an arbitrarily long board by marking off each foot length with a pencil. In other cases this limit is absolute. A bathroom scale can't be used to weigh a hippopotamus and weighing the hippo in sections is not a viable option.

Real Actuators.
Force output. If a controlled force is the desired output, then the situation is similar to that for sensors: we can have $F_{out} = f(e_{in})$ and in many cases $F_{out} = Ke_{in}$ is achievable over a limited range.

Position or velocity output. Section 2.5 showed how we can use controllable force to achieve desired values for position and velocity, where "achieve" means that we can get within some Δx of the desired value within a time Δt, where Δx and Δt will depend on the available power and the system dynamics. We will compress this description into the statement that we can control the *steady state* values of the chosen quantity.

Steady state position or velocity. If $F_{load}(x, \dot{x}, \ddot{x})$ is the force seen by the actuator then the system will have a steady state equilibrium at position x for an electrical input e_{in} if the equation $F_{out}(e_{in}) = F_{load}(x, 0, 0)$ has a solution. If $F_{load}(\dot{x}, \ddot{x})$ does not depend on x, then the solution $u(e_{in})$ to the equation $F_{out}(e_{in}) = F_{load}(u, 0)$ will be the steady state velocity for an input of e_{in}.

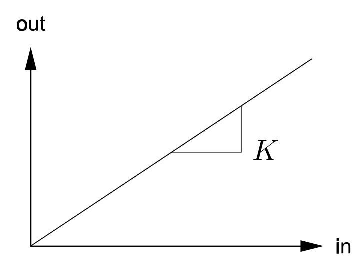
3.2 Device Characterization

3.2.1 Static Characterization

We can decouple the dynamics of a device from its static characteristics with the following calibration procedure:

1. Apply a known input.
2. Wait for the output to settle.
3. Record the resulting output.
4. Repeat with additional input values.
5. Plot the result.

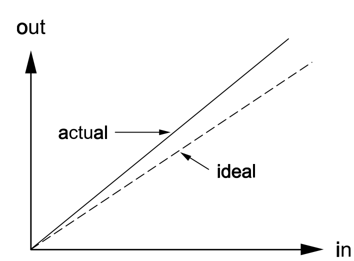
Ideal linear behavior. What we would like to see would be a nice straight line passing through the origin whose slope is equal to the value of K which was advertised for the device. This slope, $\frac{d\,out}{d\,in}$, is called the *sensitivity* of the device and for a linear device is the DC value of the transfer function (DC gain).



3.2.1.1 Linear Errors

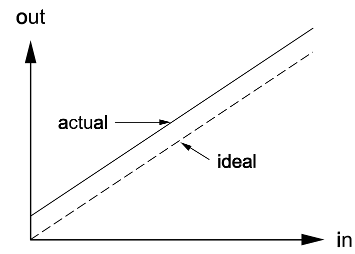
There are several ways the device could depart from its ideal behavior but still have a straight line out vs in plot.

Gain error. In this case the relationship is still linear, but the actual value of K is different from the specification.



Gain Error

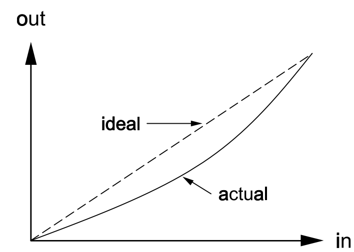
Offset. If $out = K \cdot in + offset$ we have a straight line of the proper slope, but the system is now afine, rather than strictly linear.



Constant Offset

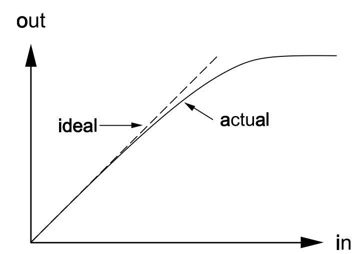
3.2.1.2 Nonlinearity

General nonlinearity. Many transduction phenomena have quadratic, inverse, or inverse square relationships.



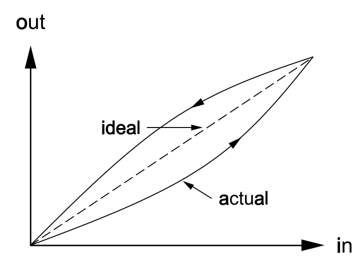
Nonlinearity

Saturation. As mentioned above, no real device can respond linearly to an arbitrarily large input without something bad happening. In some cases the relation remains linear until something melts, but sometimes the process is self limiting and after a point further increases in input produce no additional change in output.



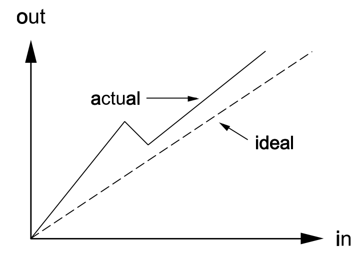
Saturation

Hysteresis. A particularly troublesome form of nonlinearity is hysteresis in which the value of the output depends upon the direction in which the input approaches its value.



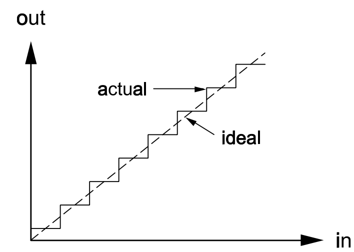
Hysteresis

Non-monotonic. A non-monotonic input/output relationship is also undesirable as the output is no longer a unique function of the input and hence the actual system state cannot be determined from the sensor signal.



Non-monotonic

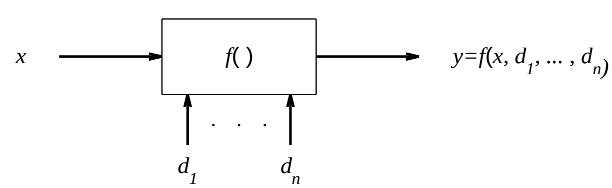
Discontinuous. While this would seem to be very bad thing, it is a fact of life for any digital sensor where the input must be quantized to convert it to a representable value. This can cause problems such as limit cycles when mechanical motion can take place without being detected by the controller.



Quantized

3.2.2 Noise and Non-deterministic Errors

Cross sensitivity. In a real device, the output will change not only in response to the intended input quantity, but also other parameters in the device's environment. These unintended inputs include changes in temperature, motions in other than the intended direction, other electrical signals, etc. The gain from one of these inputs $\frac{\partial y}{\partial d_i}$ is called *cross sensitivity.* Depending on the source of the input, the result may be unintended coupling between system variables or an uncorrelated disturbance.



Repeatability. If we apply the same input several times (approaching from the same direction to avoid hysteresis) we may not get the same output value on each attempt. One source of this lack of *repeatability* is non-linear dynamics, such as stick-slip caused by Coulomb friction.

Random noise. If we apply an input and leave it fixed, we may see variations in the output due to random noise. This is usually thermally induced and may occur in the electrical circuit or in the mechanism itself.

Slowly varying errors. A rapidly varying error is usually referred to as "noise" while slow changes in the output for fixed input are called *drift.* This is often caused by gradual changes in temperature. Another slow error is *creep* where the output completes most of the transition to a new value quickly, but covers the final distance much more slowly. This is actually a dynamic error with a very long time constant.

3.2.3 Range, Resolution, and Accuracy

Although most of the information about the static characteristics of a device is contained in its input/output plot, it is often convenient to summarize this information in a few standardized parameters.

Range. The range of input (for a sensor) or output (for an actuator) values for which the device is useful. For many types of rotational devices the range is *unlimited*.

Resolution. The smallest change in the mechanical quantity which the device is capable of measuring or producing. For "digital" devices this is usually the step size. "Analog" devices theoretically have infinite (actually infinitesimal) resolution, but hysteresis and noise may limit its useful resolution to some non-zero value.

Accuracy. Accuracy is a measure of how close a measurement comes to the actual value of the quantity being measured. It is usually described by giving the maximum value of the error, either as an absolute quantity, as a percentage of the reading, or as a percentage of the maximum (full scale) value.

3.3 Dynamic Characterization

When we change the input, the output doesn't reach its final value instantaneously, due to the non-zero masses, capacitances, inductances, etc. which are present in the system. As we saw in Section 2.3.1, dynamic behavior may be characterized by differential equations, or by the transfer function if the system is linear.

However, characterization of stand alone device dynamics can be useful. For example, if we rigidly attach a small accelerometer to a machine member having significantly greater mass, the dynamics of the machine will be largely uneffected and the response will be essentially that of the accelerometer alone. Dynamic performance may be parameterized in terms of the frequency response (e.g. bandwidth) or in terms of the step response (rise time, overshoot, settling time, etc).

3.4 Other Characteristics

Physical. In addition to having a non-zero impact on the dynamics of a system, a device will also have some other physical aspects which must be accommodated in the design. These include size, weight, and geometric considerations such as form factor.

Economic. Of obvious importance is how much the device costs to buy, but more important may be how much it costs to use. This includes running costs, which will depend on efficiency, and maintenance costs.

Environmental. Just as a device may have unintended inputs, it will also likely have unintended outputs such as acoustic noise and waste heat (also improved by increased efficiency). It may also have other undesirable environmental or safety considerations such as high voltages, dangerous chemicals, etc.

3.5 The Device Scorecard

If we were trying to buy a device to meet a design specification, we would look at the **data sheets** for products from various vendors and select the one which was the best match for our requirements. We will be studying devices with no specific application in mind, but still need a way of describing their class behavior in a succinct manner. For this we will use a generic data sheet or *scorecard* to keep track of general characteristics of each class of devices as well as representative quantitative values or ranges for specific parameters. Figure 3.2 shows some of the data we will be collecting on the different devices we encounter.

Classification	
Class Name	e.g. DC Motor
Subclass Name	e.g. Brushless
Sensor or Actuator	
Type of Motion	Rotational/linear
Intended output/Measurand	
Behavior	
Controlling input/signal output (parameter)	e.g. frequency
Defining/coupling equation(s)	
Capability	
Range	
Accuracy	
Load Rating	
Interface	
Voltage	
Current	
Impedance	
Dynamics	
Frequency Response	
Mass, τ, etc	
Physical, Economic	
Size	
Weight	
Cost	
Maintenance	
Environmental	

Figure 3.2: The Device Scorecard