Chapter 4

Transducers and Devices

4.1 Device Architecture

A *transducer* is a device which converts energy from one form to another. A *sensor* is a device which converts a physical quantity (called the *measurand*) into an electrical signal for the purpose of control or measurement. An *actuator* is a device which converts an electrical signal into a mechanical force or motion. Although we could consider sensors and actuators to be transducers, we will refer to them as *electromechanical devices* and reserve the term *transducer* for that part of the device which performs the actual electrical/mechanical conversion.

Using these definitions, a transducer whose output voltage is proportional to a mechanical displacement could be used directly as a position sensor. We could also combine it with a spring to produce a force sensor. In this case the complete sensor is made up of two components: the *sensing element* (the spring) which converts the mechanical quantity which we wish to measure (force) to another mechanical quantity (displacement) to which our *transducing element* is sensitive.
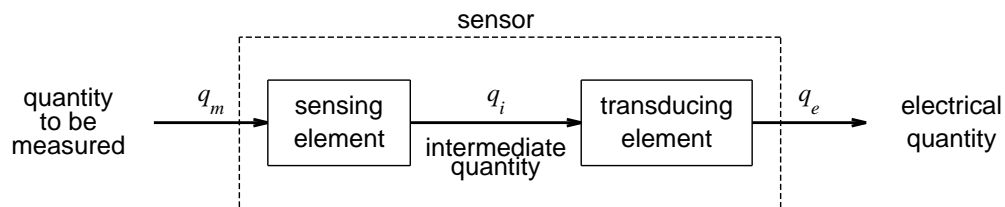

Figure 4.1: Sensor Architecture

This intermediate step could be necessary for several reasons: to extend the range of the transducer to match the range to be measured, to adapt the physical quantity to which the transducer is sensitive to the quantity to be measured.

A similar situation may arise with an actuator where the physical quantity which we wish to control is not one which we can directly produce electrically. This was the case in Section 2.5 where we needed to be able to control a position with a device which produced an electrically controlled force.

Sensing the state of a mechanical system need not remove energy from it. However, transferring that information to an electrical circuit *does* require energy. A sensor which takes this energy from the mechanical system being measured is called a *self-generating* sensor. To provide this energy, work must be done by the mechanical system i.e. motion must take place. This means that a self generating sensor cannot measure a static position. To perform such a measurement, a separate source of electrical energy must be mechanically modulated. A sensor which takes its energy from a source other than its mechanical input is called a *non-self-generating* sensor.

Actuators must do work on, and hence supply energy to the mechanical system. This energy could come directly from the electrical portion of the system or a separate energy source could be electrically modulated, as with a hydraulic actuator. But even a modulating actuator must electrically produce a small force which is then mechanically amplified.

4.2   The Plan

In Part I we identified some of the requirements a sensor or actuator must meet as part of an electromechanical system. As shown in the previous section, the core of such a device will be a *transducer* which transfers energy or information between the mechanical and electrical subsystems.

We now turn to the task of building a collection of various types of transducers which will convert voltages or currents into forces and convert forces, velocities, and displacements into electrical signals. There is a wide variety of physical phenomena which can be exploited for these purposes and we will need some sort of structure to study them efficiently.

Some texts organize devices by the quantity they produce or measure, placing motors in one chapter, velocity sensors in another, and position sensors in another. While this is a good format for *cataloging* devices, it is less well suited to studying how they work. We will group devices according to this underlying phenomena, or principle of operation, or *technology*.

Our approach will be to

1. Identify a promising phenomenon.

2. Examine its underlying physics.

3. Identify *effects* which should be useful for constructing devices.

4. Produce *prototype* or *skeleton* devices which embody these effects to produce or measure motion.

5. Develop these prototypes into workable, *real* devices.

6. Characterize the resulting devices.

Since the key to producing an actuator is to produce an electrically controlled force, we will start by examining forces of electrical origin.

4.3   Forces of Electrical Origin

The fundamental equation describing electrically generated forces is the *Lorentz force law*:

$$\mathbf{F} = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \tag{4.1}$$

which describes the force on a particle having charge q moving at velocity $\mathbf{u}$ as a consequence of the electric field $\mathbf{E}$ and the magnetic field $\mathbf{B}$. The $\mathbf{E}$ field is produced by static charge, and the $\mathbf{B}$ field by moving charge or current. The laws governing the behavior of $\mathbf{E}$ and $\mathbf{B}$ are given by *Maxwell's equations*:

Point Form	Integral Form	
$\nabla \times \mathbf{H} = \mathbf{J}_e + \dfrac{\partial \mathbf{D}}{\partial t}$	$\oint \mathbf{H} \cdot d\mathbf{l} = \int_S (\mathbf{J}_e + \dfrac{\partial \mathbf{D}}{\partial t}) \cdot d\mathbf{S}$	(Ampere's law)
$\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$	$\oint \mathbf{E} \cdot d\mathbf{l} = \int_S (-\dfrac{\partial \mathbf{B}}{\partial t}) \cdot d\mathbf{S}$	(Faraday's law; S fixed)
$\nabla \cdot \mathbf{D} = \rho$	$\oint_S \mathbf{D} \cdot d\mathbf{S} = \int_V \rho \, dv$	(Gauss' law)
$\nabla \cdot \mathbf{B} = 0$	$\oint_S \mathbf{B} \cdot d\mathbf{S} = 0$	(no magnetic monopoles)

Table 4.1: Maxwell's Equations, General Case

We will study forces due to the electric and magnetic fields separately, starting with the electric field.