Appendix C

Batteries

Robots may be powered by a variety of methods. Some large robots use internal combustion engines to generate electricity or power hydraulic or pneumatic actuators.

For a small robot, however, battery power offers a number of advantages over any other method. Batteries are cheap, relatively safe, small, and easy to use. Also, motors convert electrical power into mechanical power with relative efficiency.

There are many different types of batteries, each with its own tradeoffs. This chapter introduces a variety of batteries, explains standard ways of rating batteries, and discusses the design of the 6.270 battery charger.

C.1 Cell Characteristics

Two terms that are often used interchangeably, but actually have a different meaning, are the words *battery* and *cell*. Technically, a cell is the unit that houses a single chemical reaction to produce electricity. A battery is a bank of cells.

C.1.1 Voltage

Cells use chemical reactions to produce electricity. Depending on what materials are used to create the reaction, a different voltage will be produced. This voltage is called the *nominal cell voltage* and is different for different battery technologies.

For example, a standard flashlight cell uses a carbon-zinc reaction and has a cell voltage of 1.5 volts. Car batteries have six lead-acid cells, each with a cell voltage of 2.0 volts (yielding the 12 volt battery).

C.1.2 Capacity

In general, the larger a cell is, the more electricity it can supply. This *cell capacity* is measured in *ampere-hours*, which are the number of hours that the cell can supply a certain amount of current before its voltage drops below a predetermined threshold value.

For example, 9 volt alkaline batteries (which consist internally of six 1.5 volt alkaline cells) are generally rated at about 1 ampere hour. This means that the battery can continuously supply one ampere of current for one hour before "dying." In the capacity measurement, the 9 volt alkaline battery "dies" when the battery voltage drops below 5.4 volts.

However, the amp-hour measurement is usually taken to assume a twenty hour discharge time. Then the 9 volt battery would need to be tested by having it supply 1/20th of its rated capacity—this would be 50 milliamps—for twenty hours. If it were drained more quickly, as in the one-hour test, the capacity would turn out to be quite a bit less.

C.1.3 Power Density

There are large differences in capacity per unit weight—the cell's *power density*—across battery types. This is a of the cell's most important rating.

Inexpensive carbon-zinc cells have the lowest power density of all cell types. Alkaline cells have about ten times the power density of carbon-zinc cells. Nickel-cadmium cells have less power density than alkalines, but they are rechargeable.

C.1.4 Discharge Curve

When a cell discharges, its voltage lessens over the course of the cell life. The characteristic discharge curve varies considerably over different types of cell.

For example, alkaline cells have a fairly linear drop from full cell voltage to zero volts. This makes it easy to tell when the cell is weakening.

Nickel cadmium cells have a linear voltage drop region that then drops off sharply at some point. For this reason, when consumer products use nickel cadmium cells, the device will suddenly "die" with no warning from the cells. One minute, they are fine, the next, they are dead. For a ni-cad cell, this is normal, but it can be annoying.

C.1.5 Internal Resistance

A cell can be modelled as a perfect voltage source in series with a resistor. When current is drawn out of the cell, its output voltage drops as voltage is lost across the resistor.

This cell characteristic, called the *internal resistance*, is important because it determines the maximum rate at which power can be drawn out of the cell.

For example, lead acid cells have very low internal resistance. This makes them well suited for the application of being a car battery, because huge amounts of current can be draw from the cells to operate the car's starter motor.

Another example comes from a consumer photography flash. During the recycle time of a standard flash unit, the flash's cells are supplying charge as quickly as they can. The rate is limited largely by the cells' internal resistance. Alkaline cells have higher internal resistance than nickel-cadmium cells. Thus, the flash unit takes longer to recycle when alkaline cells are used.

Cells that have low internal resistance, in particular, lead acid and nickel cadmium cells, can be dangerous to work with, because if the cell is shorted, huge currents can flow. These currents will heat the metal wire they are flowing through to very high temperatures, easily melting the insulation from them. The cells will also become very hot and potentially may explode.

For this reason it is very important not to short a lead acid or nickel cadmium cell. Alkaline cells and carbon zinc cells, with their high internal resistances, will still deliver quite a bit of current when shorted, but nowhere near the amounts of the other two types of cells.

C.1.6 Rechargeability

Another important characteristic of a cell is whether or not it is rechargeable, and if so, how many times. Because cells are quite toxic to the environment, use of rechargeable cells is an important issue.

Unfortunately, the cells with the highest power densities—alkaline and lithium—are not rechargeable. But advances in rechargeable technologies are catching up.

The Memory Effect

The term "memory effect" refers to a phenomenon observed in rechargeable nickel cadmium cells in which cells that are only partially discharged before being recharged have a tendency to "remember" the level of discharge, and, over time, only become usable to that discharge level.

There is disagreement amongst cell manufacturers as to whether or not this phenomenon actually exists, but most concur that nickel cadmium cells should be discharged fully before being recharged.

Some cell technologies, such as lead acid cells and the new nickel hydride, do not exhibit this effect. Lead acid cells typically last for several hundred cycles of full discharge, and a thousand cycles of partial discharge.

C.1.7 Cost

Last but not least is cost. It would be wonderful if the best cells did not cost substantially more than the cells with worst performance, but this is not the case.

For consumer purposes, it is generally agreed that nickel cadmium cells, which cost several times as much as alkaline cells, are much less expensive over the cells' lifetimes. Nickel cadmium cells can be recharged several hundred times while alkaline cells are disposed of after one use. On the other hand, nickel cadmium cells exhibit the "sudden death" property mentioned earlier.

Some new battery technologies, like the very high capacity, rechargeable nickel hydride cells, are very expensive, but offer twice the capacity of either lead acid or nickel cadmium cells.

Figure C.1 summarizes the characteristics of commonly available cell technologies.

Probably the worst thing one can say about all types of battery is that "it doesn't last long enough." Unfortunately this is more or less true, but things in the battery technology field are improving. The advent of laptop computers and the need for convenient electric cars have created a real market need for improved batteries.

C.2 Battery Packs

There are two ways that cells may be combined to make batteries: series connections and parallel connections.

Cell Type	**Voltage**	**Power Density**	**Internal Resistance**	**Rechargeable**	**Cost**
Carbon-Zinc	1.5 volts	low	high	no	low
Alkaline	1.5 volts	high	high	no	moderate
Lithium	1.5 volts	very high	low	no	high
Nickel-Cadmium	1.2 volts	moderate	low	yes	moderate
Lead-Acid	2.0 volts	moderate	low	yes	moderate
Nickel-Hydride	1.2 volts	high	low	yes	very high

Figure C.1: Table of Cell Characteristics

When cells are connected in series, their voltages add but their amp-hour capacity does not. Series batteries should be composed of cells of equal capacities.

When cells are connected in parallel, their voltages remain the same, but their capacities add.

C.3 6.270 Battery Charger

Figure C.2: Battery Charger Schematic Diagram

The rule of thumb for charging batteries is to charge them at a rate equal to one-tenth of the amp-hour capacity of the battery. For example, if a battery is rated for 2.5 amp-hours (as are the Gates cells included in the 6.270 kit), then it would normally be charged at a rate of 250 milliamps.

Figure C.2 shows the schematic diagram of the battery recharger. The essence of the charger is simply a resistor in series with the battery hooked up to a regulated voltage power supply.

The resistor limits the amount of current that can be delivered to the battery as a function of the battery voltage. Suppose that the battery is at its nominal 6 volt level. Then the voltage across the resistor is the voltage supply minus 6 volts. The current can be calculated as V/R, where V is the voltage drop and R is the resistor's value.

The 6.270 battery charger allows switching between two resistors for each of the two battery charge circuits. The 15Ω resistor limits current to about 250 to 300 milliamperes for a six volt battery. This is the normal charge rate. The 7.5Ω resistor limits current to about 500 to 600 milliamperes. This is a quick charge rate and should not be maintained after the battery is fully charged.

The resistors dissipate a fair bit of energy as heat and hence must be physically large. The amount of power dissipated is measured in watts and is calculated by the law $W = V \times I$, where V is voltage across the resistor and I is the current travelling through it. Since $I = V/R$, the power dissipation rate is $W = V^2/R$.

Assume a 4.8 volt drop across either resistor (12 volt supply minus 6 volt battery level minus 1.2 volts diode drop). For the 7.5Ω resistor, the power dissipation is then $4.8^2/7.5$, which is approximately 3 watts. A 5 watt resistor was selected for use so as to allow a margin of error and to provide better heat dissipation.

A similar calculation can be made for the 15Ω resistor, for which a 2 watt rating was chosen.

The status LEDs are lit by the voltage drop across the resistor in use.

The bridge rectifier acts to polarize the voltage input, so that either an AC or DC supply can be used. It also drops about 1.2 volts from the supply as per normal diode characteristics.