Electronic Devices for the Mechanical Engineer[*]

By Nathan Delson**

Purpose of Document

Mechanical engineers are increasingly required to be familiar with electronic concepts, sensors, and controls. Microcontroller and sensor costs have dropped to the point where even the least expensive products now often have electronics in them. The incorporation of electronic elements in a mechanical design can often increase the performance and enhance the feature set of a design, often at a reduced cost compared to a purely mechanical approach. Accordingly, the capabilities of both mechanical and electronic components, and their interactions, must be considered when designing a device. A mechanical engineer may be called upon to design simple electronic devices, or to work closely with electrical engineers during a project.

The purpose of this document is to give an overview of how electronics can be incorporated into mechanical devices. This document does not replace fundamental courses in electronics, but rather brings together some practical aspects of electronic circuits and sensors that are often useful in mechanical designs.

Good Electronic Design vs. Bad Electronic Design

It is possible to hook up electronic components in an unplanned fashion and actually get a circuit to work. However, such an approach can lead to intermittent and unpredictable performance. Moreover, it can lead to hours of frustrating debugging. Good Electronic Design includes:

- Using the specifications of each electrical component to ensure that the circuit is not "asking" a component to exceed the specifications it is designed for.
- Clear drawing of all circuit diagrams ("schematics"), accompanied by current and voltage calculations where necessary.
- Step by step implementation of an electronic circuit, where the performance of each functional stage of the circuit is verified with a multimeter or oscilloscope before moving on to the next stage.
- Follow the Hands-on Guidelines for Good Circuit Implementation described later in this document. This includes using consistent wire colors and separating high power and lower power circuits. Not only will

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[*] Title inspired by Britt Rorabaugh's book "Mechanical Devices For the Electronics Experimenter"
** with review and input from Steve Roberts updated September 2010

this keep you organized, but will allow others to understand your circuit and help you debug it.

Bad Electronic Design includes:

- Copying the wiring diagram of a circuit without understanding how it works.
- Treating an electronic circuit as a magical black box which sometimes works and sometimes doesn't. If your circuit is not working, there's a reason. Use your multimeter or oscilloscope to figure out why. Not only will you end up with a reliable circuit, but you will gain the satisfaction of understanding why it didn't work, which you will draw upon the next time such a situation comes up.

Basic Terminology

Electrical vs. Electronic:

Any device that uses electricity such a motor can be considered electrical. However, when one adds semiconductor devices (transistors, sensors or control circuitry) then it becomes electronic. If you see an Integrated Circuit (IC) on a device, then it is electronic.

Electromechanical and Mechatronic Devices:

An electromechanical device includes both mechanical and electrical or electronic components. In early designs of electromechanical devices the mechanical design was typically performed separately from the electrical and electronic design. However, as electronics has become more pervasive, the mechanical and electrical design have become more tightly integrated in many products. The term *Mechatronics* originated in Japan and was introduced to describe products where both the mechanical and electronic design must be considered concurrently for optimal performance. The term electromechanical is more widely used, but the term Mechatronics is gaining recognition.

Consider a simple oscillatory fan used to ventilate a room. The propeller, housing, and bearing design could all be done by a mechanical engineer. An electrical engineer could then design the motor wiring and on/off controls with only general specifications from the mechanical engineer. I would consider such a device as electromechanical.

Now consider a fan used for cooling the microprocessor on your PC. The fan speed controller often includes circuitry to sense the temperature of the microprocessor, and adjust the fan speed up or down using Pulse Width Modulation (described later), so that high fan speeds are only used when necessary, thus minimizing power consumption and reducing noise. The design of such a fan would require close coordination between mechanical and electrical engineers. I would consider this a Mechatronic application.

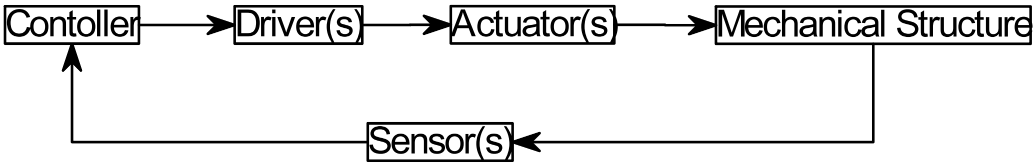
Hardware:

The term “hardware” is used in various fashions. Electrical Engineers use the term “hardware” for electronic circuits, while using the term “software” for the control algorithms running in a microcontroller (often their deliverables do not include moving mechanical parts so a complete EE project can be separated into hardware and software components). On the other hand, Mechanical Engineers often use the term “hardware” to refer to mechanical components, while considering electrical components and control code as a separate item. Once can avoid confusion by using the terms “mechanical hardware” and “electrical hardware.” However, due to the multidisciplinary nature of electromechanical devices, one will encounter this ambiguity. Just remember that each engineering discipline comes from a different perspective, but we all have to work together to get our “hardware” to work!

Components of Mechatronic Devices

Block Diagram of a Mechatronic Devices:

The basic components of a typical Mechatronics device are shown below



Controller:

The controller could be a small microcontroller, a high-powered processor like a Pentium class device, or one of the many custom chips used for control. The controller acquires sensor data, makes decisions based on the control algorithms it is running, and specifies commands to the drivers. Microcontrollers have built in non-volatile memory, so that one can download and save a program to it. Microcontrollers are generally low-power devices, often running on batteries unattended for long periods. High-end microprocessors can use substantial power, as attested to by the heat built up in a laptop computer. Key characteristics of a microcontroller are:

- Input/Output (I/O)
  - Digital I/O is high or low voltage corresponding to 1 or 0
  - Analog input which can be read with Analog to Digital (A/D) convertor and allows measurement of a range of voltages
  - Pulse Width Modulation (PWM) with simulates an analog output (more on this later).
- Calculation speed
- Memory
- Power consumption. Many battery operated devices use very low power microcontrollers.

Alternative control approaches include analog operational amplifiers (*op-amps*) or digital circuits made with combinations of logic chips. However, with the current low cost of microcontrollers, most Mechatronics devices include one or more microcontroller where software can be easily updated to modify controller performance without changes in the circuit.

Sensors:

A sensor typically produces a change in some electrical property (resistance, capacitance, voltage) in response to some physical property, including such properties as color, distance, velocity, temperature, or presence of an object. Sensor technology and sensor applications have increased tremendously over recent years. Examples include Microelectromechanical systems (MEMS) such as the miniature accelerometers used to deploy airbags in automobiles, capacitive sensors that detect whether cornflakes have settled too much in a box, and optical sensors that detect if there is a green blueberry that needs to be removed from a canning process. Sensor development is a very active field, and if there is a physical property of importance, there most likely is someone working on a better way to sense that property. Sensors typically use low (or no) power.

Actuators:

An actuator transfers mechanical energy into a system. In a Mechatronic device the energy transfer is typically electrical energy into mechanical energy. Example actuators include: motors, pistons, and solenoids. The power requirements of an actuator can be quite high. Of course, smaller actuators such as the vibrator in a pager consume relatively little power. Because motors are perhaps the most common actuators in Mechatronic devices, many engineers simply use the term motor, rather than the more general term actuator.

There are many types of actuators. Motors alone include brushed DC motors, brushless DC motors, AC motors, linear motors, and stepper motors. Reduction in cost of rare earth magnets, advances in magnetic modeling, and low cost motor drivers have produced new types of actuators in recent years. A

Mechatronics engineer needs to stay abreast of the capabilities of different actuators.

Since actuators perform physical work on the environment, they require electrical power in proportion to their physical power output. A key characteristic of actuators is that they require relatively high levels of electrical power to operate, much higher than most sensors.

Device Drivers (e.g. motor drivers) :

Because actuators typically require high power, and microcontrollers are low power devices, one usually needs a *Device Driver* to power an actuator (see block diagram above). The driver receives its input from the microcontroller, and then uses power from an electrical source to operate the actuator. The simplest driver can provide on/off control of an actuator. More sophisticated drivers allow for variable speed or torque control (more on this later). A common beginner's mistake is to connect the microcontroller output directly to an actuator, not realizing that the microcontroller cannot output sufficient power to drive the actuator.

To add to the confusion, some driver manufacturers refer to their devices as controllers, since from their perspective their device controls the motor.

A common feature of all device drivers is that they can turn on and off high current signals, from low current commands. Typically the low current commands are generated from a microcontroller. Examples of Transistor and Relay drivers are further in this document.

Electronic Background Required

This document does not replace a fundamental course in electronics and assumes that the reader is familiar with:

Ohm's Law:

The voltage drop across a resistor is given by:

$$V = I R$$

Where, V is voltage in volts, R is the resistance in ohms, and I is current in amps.

Power Dissipation:

Power dissipated in a resistor or other electrical component is given by:

$$P = V I$$

Where, P is power in Watts, V is voltage drop across the component in volts, and I is current through the component in amps.

Kirchhoff's first rule:

The sum of all currents entering a branch point of a circuit (a *node* where three or more wires merge) must be equal to the sum of the currents leaving the branch point. This simply says none of the electrons get lost or fall out of the wire.

Kirchhoff's second rule:

Around a closed loop in a circuit, the sum of all the voltage drops must equal zero.

Circuit Dynamics:

We will not cover circuit dynamics in-depth in this document. Most of our applications will involve *DC circuits*, where the many types of circuit dynamics which are important in *AC circuits* will largely play only a minor role for us. However, one should have a general understanding of capacitors and inductors. One should be familiar with the behavior of RC circuits.

Voltage vs Current:

Voltage is measured as the potential energy ***difference*** between two points in a circuit. ***Ground*** is often one of those two points. Voltage can be ***easily*** measured with a voltmeter or oscilloscope, and good designers are always measuring voltage at points throughout a circuit. An **ideal voltmeter** has infinitely high *input impedance*, and thus does not disturb the circuit being measured because it **draws virtually no current**. For many circuits, including those we will be building, even a cheap handheld digital multimeter can be considered ideal.

Current is measured ***through*** a device. Current is ***hard*** to measure; it requires taking apart the circuit and ammeters often are limited in the amount of current they can measure. Because current is harder to measure, a beginner mistake is to ignore current in circuit debugging, yet it is one of the largest causes of circuit failure. A good designer estimates the current in a circuit through voltage measurements. An ideal ammeter has no internal resistance.

Multimeter vs Oscilloscope:

Multimeters are inexpensive and easy to use; however, they are slow and average readings over a second or more. In electronic devices small glitches or noise can cause significant havoc with microcontroller logic. To see such glitches, one needs the high speed response of an oscilloscope. So if you cannot figure out why a circuit is not working after reviewing it with a multimeter, then fire up the scope!

If you forgot how to use an oscilloscope, take the time to familiarize yourself. Always ground the probe on your circuit, since your breadboard may not be grounded relative to the wall ground. Remember to look at the voltage and time scale, otherwise small noise on a constant signal can look huge. Scope these days are digital which means they have a wide range of features but one needs to learn how to scroll through the menus. Also, digital scopes are not as fast to respond as the old analog scopes, so one needs a bit of patience when looking at signals.

Multimeter Use Tips:

- The most common setting is on DC volts. This allows you to probe a circuit without effecting the circuit.
- If you ever do make current measurements, make sure that the setting and lead connection is in the correct current range. Otherwise you can dame the multimeter.
- The ohm meter sources current from the battery the meter into the leads. This works fine for measuring resistors that are disconnected from a circuit.
    - DO NOT use the ohmmeter to measure a component that is connected to the rest of the circuit, since it will be sending current throughout the circuit. Your measurement values will be wrong and you may damage the circuit.
    - DO NOT use the ohmmeter to measure active components such as ICs or LEDs, the current from the meter may damage them.

Importance of Power in Electronic Components

The law of energy conservation dictates that energy needed to drive a component cannot come from thin air. Since there is always some energy loss, one needs to supply each component with a minimum amount of energy it needs to operate. Power is the use of energy over time, and thus the power requirements is one of the more important factors needed to size a component. (this is true of both mechanical and electrical components). These requirements will be specified on the data sheet which describes the component, and is one of many good reasons to read the data sheet before applying a component in your circuit.

Each electrical component also has a certain efficiency. If you pass a large amount of current through a device it can heat up! If a device overheats it will either burn out, or shut down due an internal thermal protection device. An example: Say you want to control the speed of a motor by passing the motor drive current through a transistor. At the voltage you will run the motor the maximum current is, say, 3 amps. You design a circuit and select a power transistor which for which the short product description states that the device can handle 6 amps of current. Great; no problem! However, the fine print in the data sheet will say that a heat sink must be used to realize that current-carrying capability. You build your circuit and the motor works fine for about 15 seconds, and then stops. Something smells like it's burning, and you realize the transistor is super hot! Another good reason to read the data sheet…

Another common misstep is attempting to power a motor, a solenoid, or some other high-current device with an insufficient current source. Say you have a 5-volt motor. A microprocessor also runs on 5 volts, and can produce 5 volts on its output pins. So we can run and control the motor simply by wiring it to an output pin on the microprocessor. Great, this is easy! You write your program, carefully hook everything up, and run the program. But…   the motor doesn't go, it seems like the microprocessor has stopped, and it's kind of hot.

Every electronic component is limited in terms of power in either:

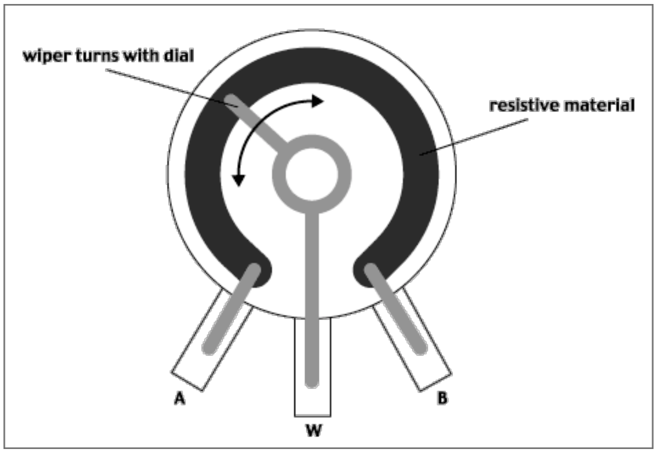
- Amount of power it can output.
- Amount of power that can be transferred through it.
- Amount of power it needs to operate

Long story short: All electronic components have voltage and current requirements and limitations. This applies to both the required ***voltage and current*** needed to operate the component correctly, and also to the maximum allowed voltage and current which may be applied to the device by other parts or components in your circuit. Please…   Read the data sheet!

Low Current Circuits You Need to Know

Potentiometer input as a Voltage Divider

Objective: Create an adjustable voltage that can be read by a voltage-measuring device, such as a voltmeter or microcontroller. Applications include testing of an Analog to Digital input, or use with a comparator. A secondary objective is to avoid excessive energy loss. A potentiometer is a variable resistor when a knob moves a wiper across a resistive element to change the length of the electrical path from one lead to another lead. As shown below the resistance between lead A and W will be smaller than the resistance between lead W and B. Note, the resistance between leads A and B do not change as the dial is rotated. To avoid damage to high-end pots, do not measure the resistance between W and another lead with an ammeter, since the current from the ammeter may damage the resistive element if the know is all the way at one end.



Single turn Rotary Potentiometer (Figure from Mark Allen)

Potentiometers can vary in cost from less than $1 to over $100, based on mechanical smoothness, precision, current capacity, and environmental robustness. Wire wound pots are common, but can have discrete jumps in resistance as wiper slides from one coil to the next. Conductive plastic provides better resolution, but usually have lower current capacity.

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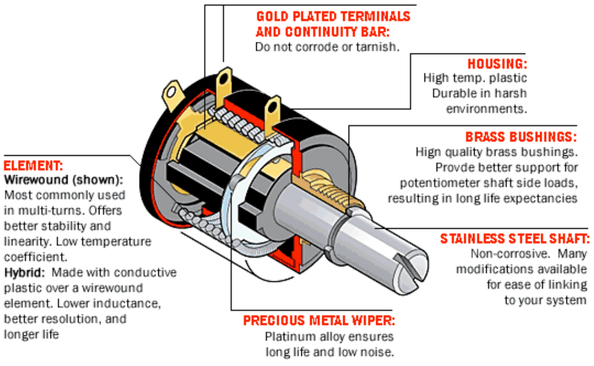
<td>
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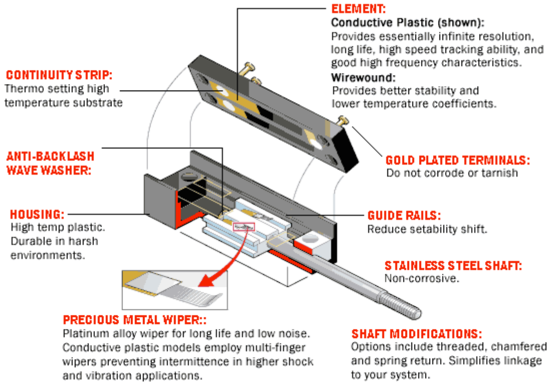
<td>
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<tr>
<td>Wire wound rotary pot</td>
<td>Linear conductive plastic pot</td>
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<td colspan="2">Figures from www.etisystems.com</td>
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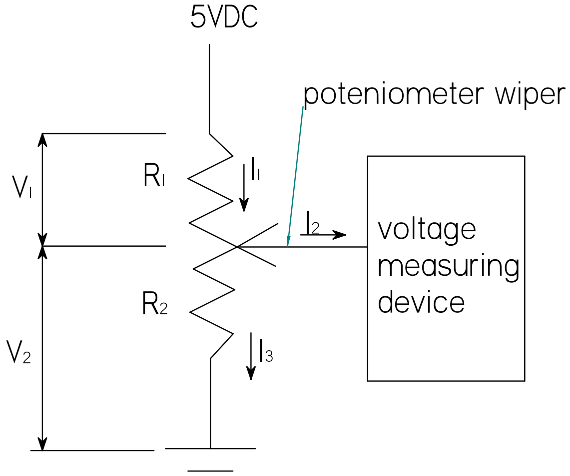
Proper connection of a potentiometer to generate a variable voltage input is as a voltage divider as shown below. The wiper is drawn as a line that could move up or down depending on the posting of the knob of the opt.



Potentiometer connected as voltage divider

Current and Voltage Calculations Assume:

- Supply voltage of 5VDC
- Ideal voltage-measuring device (i.e. it draws no current)

Kirchhoff's first rule:

$$I_1 + I_2 = I_3$$

Since voltage-measuring device draws no current, $I_2 = 0$, and thus:

$$I = I_1 = I_3$$

Ohm's Law: Voltage drops across each resistor

$$V_1 = I * R_1$$
$$V_2 = I * R_2$$

Ohm's Law: Voltage drops across both resisters in series

$$5 = I * (R_1+R_2)$$

Kirchhoff's second rule:

$$5 = V_1 + V_2$$

The voltage at the measuring device is equal to V_2, which is given by combining the above equations as follows:

$$V_2 = 5 * R_2 / (R_1+R_2)$$

Thus, as the pot wiper is moved up the measured voltage approaches 5VDC, and as it is moved down the measured voltage approaches 0.

The question remains, what should the total value of the pot be ($R_T=R_1+R_2$). The current through the pot is given by:

$$I = V/R_T = 5/R_T$$

The amount of power used by the pot is given by:

$$P_{pot} = V * I = V * V / I = 5^{\wedge 2}/R_T$$

One easy way to select the pot value, is to arbitrarily set the current through the pot to a low value of 1 milliamp (mA), a good number for a sensor level current draw). In this case:

$$R_T = V/I = 5/(1e\text{-}3) = 5{,}000\Omega$$, usually stated as “5k”

In this case the total power used by the voltage divider is relatively small:

$$P_{pot} = V * I = 5^{\wedge 2}/\ 5000 = 0.005 \text{ Watts or } 5 \text{ milliwatts (mW)}$$

One could try to reduce power consumption by increasing the potentiometer value to a very high resistance. However, extremes values will cause the non-ideal characteristics of the voltage measuring device to come into play. Lets assume we use voltage divider as an analog input to a Microprocessor. If we assume a voltage measuring device with an input impedance of 1 Meg ohm, the maximum amount of current flowing into the microprocessor would be:

$$I_2 = 5/1e6 = 0.5e\text{-}6 \text{ Amp}$$

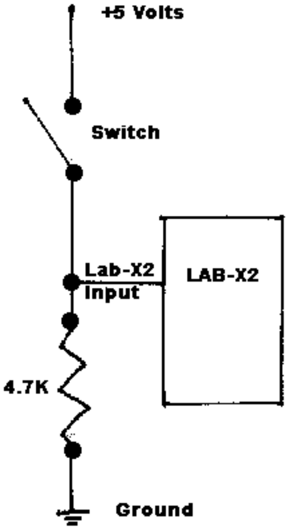
As long as $I_2 << I_1$ then our assumptions of an ideal voltage measuring device remain valid. Since the value of I_2 calculated above is 2000 times smaller than the 1mAmp selected for I initially, we see that our initial selection of a 5KΩ pot is OK. Indeed, we could select a *somewhat* larger pot and reduce our energy loss even more. However, excessively large voltage divider resistances on the order of Mega ohms, will begin to reduce the voltage measured by the A/D converters and become more susceptible to noise pickup.

As a rule of thumb, voltage dividers intended as inputs to the A/D converters on many microprocessor should have a total resistance less than 20k ohms. Inaccuracies may result if larger resistances are used.

Some questions: Could we use a voltage divider to provide a reliable adjustable voltage source for a motor? What type of problems might we encounter?

Hooking up a Switch as a Digital Input

Even a simple application as an on/off switch requires proper consideration of voltages and currents. A key consideration is to avoid a so-called *floating* input, where the connection on an input/output (I/O) pin on a microcontroller is left to “float”, i.e. it is not connected to any voltage or ground. In such a case, the apparent voltage level *seen* at the I/O pin is indeterminate, and could take on any value, almost certainly leading to system faulty operation of your program code. A proper way of hooking up a switch so as to avoid this problem is:



A switch hooked up To generate 0V input when open and 5V input when closed. The 4.7k resistor to ground defines the voltage at the input pin when the switch is in the open position.

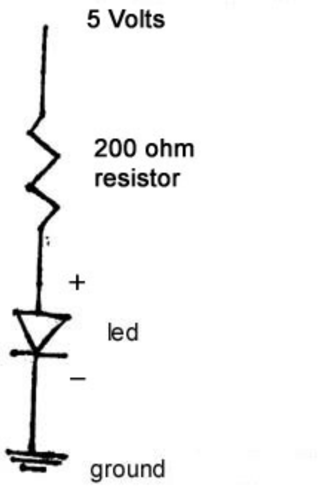
- When the switch is not pressed the Lab-X2 microcontroller will *see* 0 volts. This is logic level false or logic zero. This is because the voltage drop across the resistor is zero volts. You can verify this by measuring it with a multimeter.
- When the switch is pressed down the Lab-X2 will *see* 5 volts. This is logic level true or logic one. Now if you use a multimeter you will measure a 5 volt drop across the resistor.
- The 4.7K resistor is there to prevent the input from *floating* and to create a very simple circuit. The value of the resistor is chosen so that only a small amount of current ($I = V/R = 5/4700 = 1$ mA) will flow from the Lab-X2 (not too much (it can actually supply up to 25 mA) to drain the it, but enough to keep the input from floating).

Questions:

- Why do we need the resistor at all? Why can't we just connect the input pin directly to ground, and thus define the zero volt state when the switch is open?
- Can you think of a way to connect a switch, similar to the one shown above, but in such a manner that an open switch provides a 5V voltage input to the microcontroller, and a closed switch provides 0 voltage?

Hooking up a Light Emitting Diode (LED) to a Digital Output Pin

Hooking up an LED properly requires that one become familiar with the product spec. sheet. A key specification is that the maximum continuous forward current is 40mA, and that they typical voltage drop across the LED is 1.7V. The circuit below achieves this.



An LED hooked up within spec from a 5V digital output

Can you answer?

- What will happen if you use a lower value resistor?
- What will happen if you use a higher value resistor?

Note: LEDs are *current-driven* devices that have a mostly fixed voltage drop across them. Accordingly, one needs to choose the appropriate resistor based upon the power supply so that the current is limited to what the LED data sheet allows. If one hooks up an LED directly to a power supply with a voltage even slightly higher than the voltage drop across the LED, it will fry. Due to manufacturing variations, the voltage drop across an LED may vary slightly; therefore, one almost never drives an LED without a resistor in series.

Controllers and Digital Logic

A microprocessor is a digital device, meaning that all internal values are represented as 0s (logic level low) or 1s (logic level high). To communicate with the rest of the world, one needs to specify corresponding voltage levels. The X2 microcontroller board uses the follow voltage guidelines for logical inputs:

Low: 0 to 0.8V
High: 2.0 to 5.0V

Note, that voltage values of 0.8 to 2 V are not defined. Indeed the X2 microcontroller may work with those inputs (usually reading high above 1.3V), but the manufacturer does not guarantee this. The most robust designs will avoid inputs in this ill-defined range.

To read an analog voltage output from a sensor, you connect it to one of the analog-to-digital converter (ADC) channels on the X2 board. The voltage must be in the range 0-5 VDC.

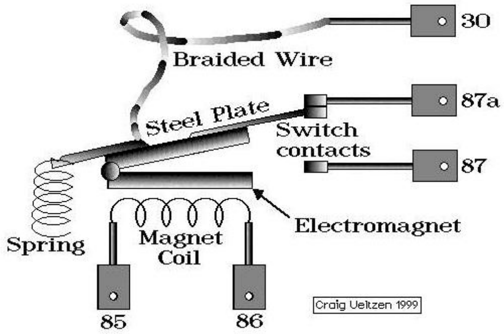
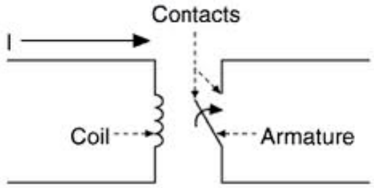
In contrast to reading in an analog voltage input which varies continuously over the range 0-5V, a microcontroller can only *output* discrete high or low logic levels (5V or 0V). One can synthesize analog voltages if desired. One approach is to use an external device called a Digital to Analog converter (DAC). Another often-used approach is pulse width modulation (PWM) in conjunction with a small RC filter, as described below.

If you ever measure a voltage output from a microcontroller digital pin that is not near 5 or 0 voltages, most likely you are exceeding the spec of the chip, and asking it source (send current out) or sink (draw current in) an amount that is in excessive of its current specification. Fix your circuit!

Controlling Actuators (higher current devices)

At some point in a Mechatronics device, one will want to turn on a motor or other such device that uses more electrical power than can be provided directly from a microprocessor. Driving any load over a few milliamps cannot be done directly from a digital output. There are two general options; relays and transistors.

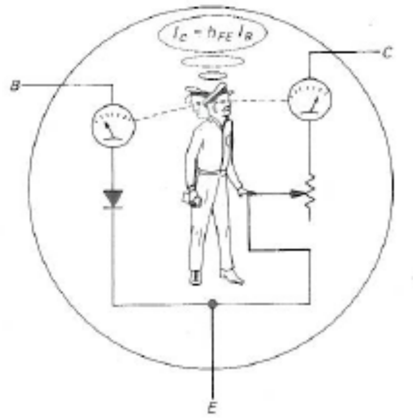
A relay is a mechanical switch activated by an electromagnet. A smaller current can operate the electromagnet, which closes a switch that can carry much larger current. See figure below.

	
Inner workings of relay (from www.classictruckshop.com)	Common representation of Relay (from zone.ni.com)

Pros and Cons of a Relay

- Old and reliable technology
- Control of very high current possible with a small current.
- Slow switching times compared to transistors (cannot be used for PWM)
- Can only be on/off, no intermediate level of control
- No voltage drop across it (i.e. provides full voltage to load)
- You can recognize a relay by the "click" it makes when the contacts close, which you hear when headlights are turned on or off in a car.
- Very good isolation between the input (control) and output (load) circuits.
- Not susceptible to damage from inductive voltage spikes.

A transistor is a semiconductor which can either conduct or not conduct (hence the name semiconductor), based upon a small amount of input current. The action of a transistor is represented by "Transistor Man" below who monitors a small current on the left, and adjusts a large current on the right.



Transistor Man. Figure from Art of Electronics by Horowitz and Hill (the bible of practical electronics)

Pros and Cons of a Transistor

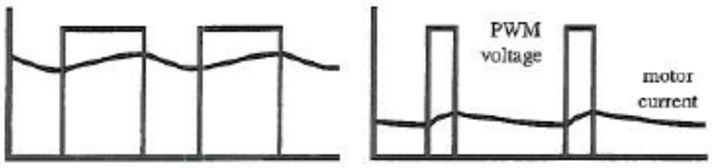
- Fast on/off times
- Level of power can be adjusted by rapidly switching on and off (see PWM below)
- Easily controlled from a microcontroller pin.
- Does have a voltage drop so not 100% of voltage used to drive load.
- Dominant method of real-time control.
- Cannot control AC current.
- Often requires a heat sink if operating at higher currents.
- Can be damaged by inductive voltage spikes or electrostatic discharge.

Modulating Power (PWM is the way to go)

A key advantage of transistor control is that one can adjust the amount of power sent to a motor or other load, thus allowing speed or torque control. There are two fundamental methods of modulating the power:

- Op Amp/Linear Control. An op-amp provides a continually varying output, however it has significant heat loss in the electronics. Op-amp are using in audio amplifiers for high fidelity, but the components are expensive heavy and large. Most control applications have been replaced by PWM (see below).

- Pulse Width Modulation (PWM) takes advantage of characteristic of semiconductors. There is much less heat loss in a transistor when it is all the way on or all the way off. The PWM approach turns the voltage on and off very quickly (thousands of times a second). Since the motor cannot start and stop that quickly the net effect is that the power to the motor is based on the percent duration that the voltage is on, i.e. the width of the pulse as shown below:



high duty cycle

low duty cycle

PWM signals at high and low duty cycles

With the PWM approach the microcontroller output is used to drive the transistor (which drives the actuator) with a series of 0-5V pulses; a pulse train which consists of a PWM signal with a duty cycle controlled by the microcontroller. In this situation, because the transistor is either driven fully on, or fully off (saturated mode), there is very little energy dissipated in the transistor itself, allowing it to pass large currents without overheating.

Hands-on Guidelines for Good Circuit Implementation

Building electronics can be a fun experience with frequency joy associated with working circuits and hardware. Or it can be a frustrating experience where it seems like circuits only work intermittently depending on the alignment of the stars. While in reality there is always some frustration in getting hardware to work, developing a systematic approach to building, testing, and debugging will serve you well throughout your career, and eliminate numerous hours of frustration. Below are some guidelines to follow.

Voltages Current and Power

- Voltages can easily be measured with a voltmeter or oscilloscope, but currents are harder to measure (you have to take the circuit apart).
- Therefore you should measure voltages, but calculate current.
- Do not ignore current since they indicate power (P=VI).
- Every electronics or electrical component has power input and output specifications
  - There is a minimum amount of power (and current) that every component needs to operate. This power is much higher for components that do significant work such as motors and electromagnets, and much smaller for logic components like a microprocessor.
  - There is a maximum amount of power (and current) that every component can output. This current is generally small for logic chips, and higher for power transistors or some op amps.

General Tips for Using Integrated Circuits

- Do not leave inputs floating (i.e. no specified voltage)
  - use a pull-up or pull-down resistor for inputs that will change
  - tie constant inputs with high (Vcc) or low (ground)
- Use capacitors to filter noise (often one places the capacitors as close as possible to filter location, since long copper wires in a circuit have a small amount of resistance which can reduce the effectiveness of a capacitor.

Develop Good Wiring Habits

- Follow color guidelines, especially for the power supply (Vcc) and ground
- Keep the wires neat (don't create a nest with too much extra length)
- Use strain reliefs in any wires that attach to moving parts or may be pulled
- Avoid shorts. Use electrical tape and shrink wrap

Debugging Skills

- Debugging is an Art and skills can be developed
- Be systematic and isolate components
  - get each component to work separately before integrating
- Use a voltmeter (and oscilloscopes for fast changing signals) to measure voltage at all points in circuit
  - If the voltage out of a logic device is less than the high voltage (typically 5V) then one is trying to draw too much current from device.

Electronic Do's and Don'ts

Have organized wiring.

-While signal wires (blue, green and yellow) can be somewhat interchangeable **make sure** that RED=+5V; BLACK=Ground; White=7.2V.

-If your wiring is messy and you ask for help, we may ask you to rewire it in a more organized fashion. We're not being mean, often the problem is found as the wiring is cleaned up.

Have a circuit diagram.

-Make it clearly labeled.
-If you update your circuit, update the diagram too.
-We will also ask for circuit diagrams.

Make good connections.

-Have strain relief on moving electronics so you do not get pull out.
-Solder things together and use heat shrink tubing to avoid shorts.

Make electronics accessible to swap out components

Test each component in sub-units so that you can be confident it works when thrown together

Measure a lot (With a multimeter or the oscilloscope)

-Voltmeter will be your friend, and if not it should be.
  -Measure the across the system to get the voltage.
  -Make sure you are in DC mode.
-Ohmmeter is handy if you don't remember color codes.
  -**DISCONNECT** the item in question from the circuit. (If not it won't work and might damage sensitive electronics)
  -Passive components only please.
-Ammeter can measure the current going through components.
  -You must measure in series to get a useful reading.

References

"The Art of Electronics" by Horowitz and Hill. Considered by some to be the "bible" on electronic design.

Physics 122 Lecture Notes, by Frank L. H. Wolfs, University of Rochester
http://teacher.pas.rochester.edu/phy122/New_Lecture_Notes/