
# Analog Microcosm

## 6.101 Introductory Analog Systems Laboratory
## Final Project

Abstract:

*The Analog Microcosm is a self-sufficient biodome capable of controlling its environment. The four elements that the Analog Microcosm regulates are temperature, lighting, humidity, and gravity. The temperature control system allows both heating and cooling and regulates the internal temperature of the biodome to a temperature set by the user. The lighting system allows the biodome's internal light to emulate the sunlight outside the biodome. The humidity control system allows humidity level to be controlled via an ultrasonic transducer. The gravity control system is a small-scale regulated centrifuge. The biodome can be a useful testing environment for various research projects as well a micromanaged habitat.*

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May 13th, 2004

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# 1 Analog Microcosm Overview

The Analog Microcosm consists of four independently controlled systems. Each of the four systems, heating, lighting, humidity, and gravity, involves the user's setting some environmental condition.

The temperature control system regulates temperature through a peltier device. The voltage to the peltier device determines whether heat is transferred into or out of the biodome from the peltier. A user sets a desired reference temperature for the internal environment of the biodome. After the user has set his or her temperature setting, the heating control system will heat or cool the biodome until the biodome's internal temperature matches the user's desired temperature. The temperature control system is the most power-demanding system of the biodome.

The lighting control system allows the lighting inside the biodome to mimic lighting conditions outside the biodome. The lighting control system involves a small remote that senses external lighting conditions and then transmits the data to a main controller. The biodome uses a 60W incandescent lightbulb, which is powered from the AC wall mains and is dim-controlled by the lighting control system.

The humidity control system generates a cool mist of water vapor when the humidity generator is active. The humidity generator is run by an ultrasonic transducer, which causes a standing wave on the surface of a column of water. Under heavy excitation, water molecules are ejected from the surface of the water column in the form of a mist. Contrary to common thermal humidifiers, the ultrasonic humidity generator is able to produce cool water mist without affecting the temperature of the biodome. The humidity control system also displays the humidity level inside the biodome for the user's reference.

The gravity control system is comprised of a motor driving a centrifuge. Two platforms hang from the centrifuge and are slowly accelerated to the user's desired gravitational setting. The gravity control system prevents objects resting on the centrifuge platforms from slipping despite acceleration. The gravity control system is capable of driving the biodome to over 40g's of gravity.

The biodome's four systems draw power from two different power supplies. The control power supply is a voltage regulated and current-limited power supply that gives power to opamps and other low-current components. The high-current supply is an unregulated supply that delivers current to the peltier, humidifier, and motor.

Ji Zhang concentrated on the design of the temperature and lighting systems, and Adam Kumpf focused on design of the humidity and gravity control systems. The power supplies, circuit debugging, and mechanical construction were a joint effort. Much of the mechanical assembly of the biodome was done at the Laboratory for Electromagnetic and Electronic Systems while the circuitry was done at the sixth floor Electrical Engineering Lab.

# 2 Temperature Control

## 2.1 System Overview

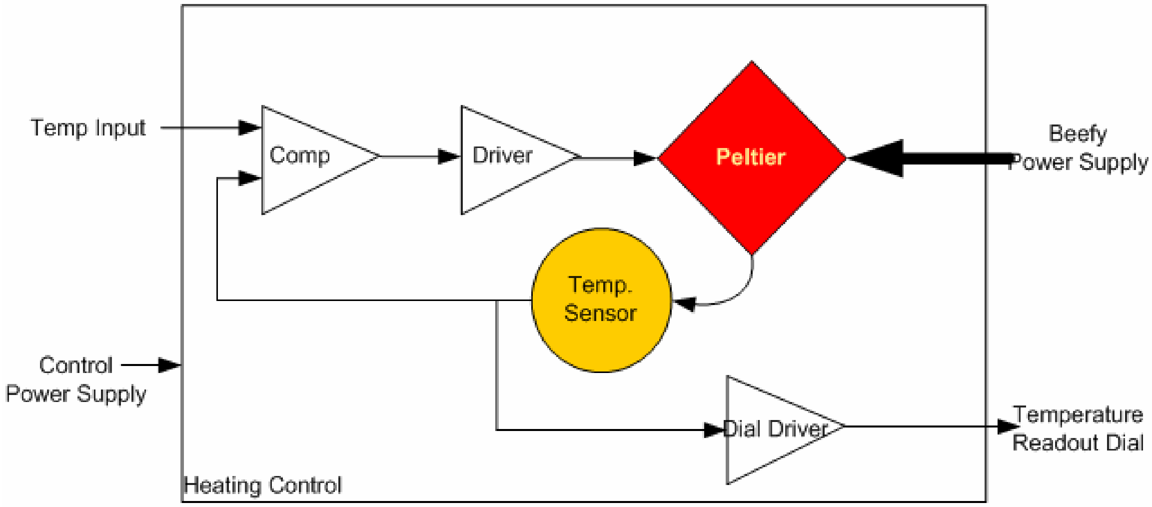



**Figure 2.1** Temperature Control Block Diagram

The temperature control system is designed to regulate the internal temperature of the biodome. The user should be able to set a desired temperature, and the biodome should automatically adjust its internal temperature to match that user's desired temperature. Afterwards, as long as the user's desired temperature is not changed, the biodome keeps its temperature constant.

Looking at the Figure 2.1, the block diagram of the temperature system, a comparator controls the user's temperature input to the internal temperature of the biodome. The internal temperature is measured through a thermistor, which is labeled as the temp. sensor in the block diagram.

By using a Peltier block, the temperature control system can both heat and cool the biodome, depending on the polarity of the voltage applied across the Peltier. Two heatsinks with fans clamp the peltier so that thermal energy can be transferred off the Peltier (see Figure 2.2). A hole on the biodome wall allows the Peltier heatsink assembly to be mounted such that the two heatsinks lie on the inside and outside of the biodome.

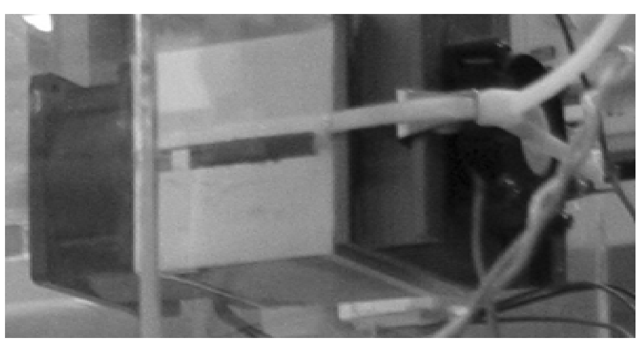


**Figure 2.2** Peltier sandwiched by two heatsinks attached to a biodome wall.

The reason that a current driver is needed between the temperature comparator and the Peltier is that the Peltier can consume up to 8 amperes of current. The comparator is an opamp that can supply some milliamps of current at the most. In addition, the Peltier draws its hefty current from a high-current supply. Since the high-current supply is expected to have a substantial ripple on its output voltage, control circuitry such as the temperature comparator should not receive power from the high-current supply. Instead, the temperature comparator draws its power from a much cleaner but less powerful power supply.

The last part of the heating system is an interface that drives an LED bar graph to display the user's desired temperature and the state of the Peltier (see Figur 2.3). The desired temperature LED bar graph (on the left, green) moves up and down according to the temperature input by the user. The user reference temperature is controlled through a knob-potentiometer on the right hand side of the board. The peltier status indicator (bottom middle, red) displays high when the peltier is heating and low when the peltier is cooling on the inside of the biodome.

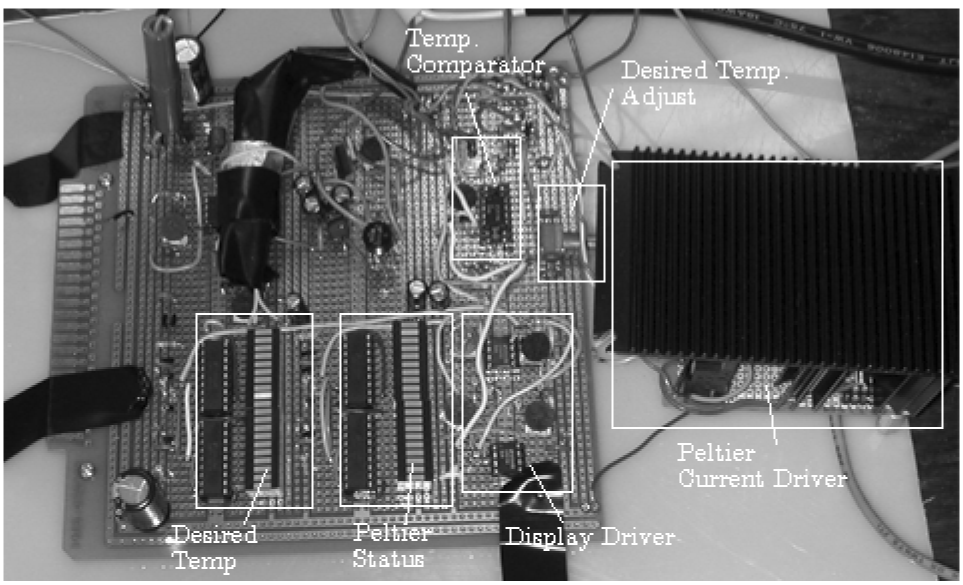



**Figure 2.3** Temperature Control Layout

## 2.2 Temperature Control Circuit

### Comparator

The comparator of the temperature control circuit is a LF356 opamp (see Figure 2.4). The positive input is the output of a voltage divider formed by a 5K resistor and a 10K thermistor. The negative input is the output of a voltage divider formed by a 2K resistor and a 10K rheostat. The JFET input LF356 is selected as the temperature comparator for its precision when compared to a common LM741.

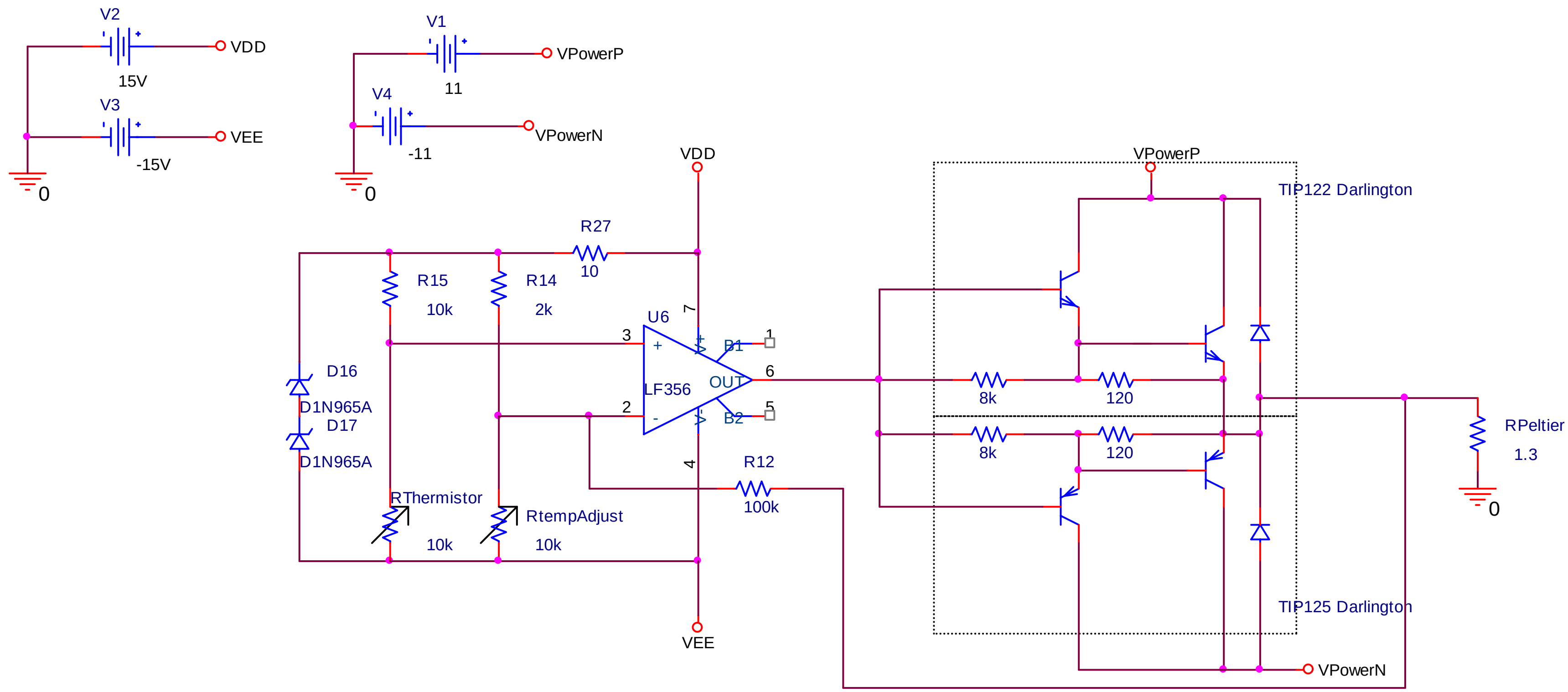



**Figure 2.4** Temperature Control Circuit
Bypass capacitors (470uF to .1uF) have been placed around the circuit,
especially at opamp rails, are not shown.

The output of the LF356 ultimately translates into an approximate voltage that drives the Peltier; henceforth, a positive output on the comparator ideally results in more heat input into the biodome and a negative output on the comparator ideally results in more cold input into the biodome.

As the temperature inside the biodome increases, the resistance of the thermistor decreases. This results in a decrease in the positive input to the opamp. If the positive input to the opamp becomes less than the negative input to the opamp (that is, if the temperature inside the biodome has risen above the desired temperature, which is input into the negative input of the opamp), then the opamp will output a negative voltage and start cooling. Likewise, when the temperature inside the biodome is colder than the desired temperature, then the positive input will be greater than the negative input to the opamp, and the more heat will be applied to the biodome.

The gain of the comparator is regulated by the 100K rheostat connecting the output of the entire temperature control system to the negative input to the comparator. The sensitivity of the temperature controller is controlled through this feedback resistance. The actual resistance used for this system is obtained empirically (see the section on Observations & Measurements).

### Thermistor Linearization

One issue with the temperature control is that the thermistor's resistance decays and grows exponentially with temperature. The standard equation for negative temperature coefficient (NTC) thermistors is

$$R_T = R_{25C}\, e^{\left\{\beta\left[\left(\frac{1}{T+273}\right)-\left(\frac{1}{298}\right)\right]\right\}}$$

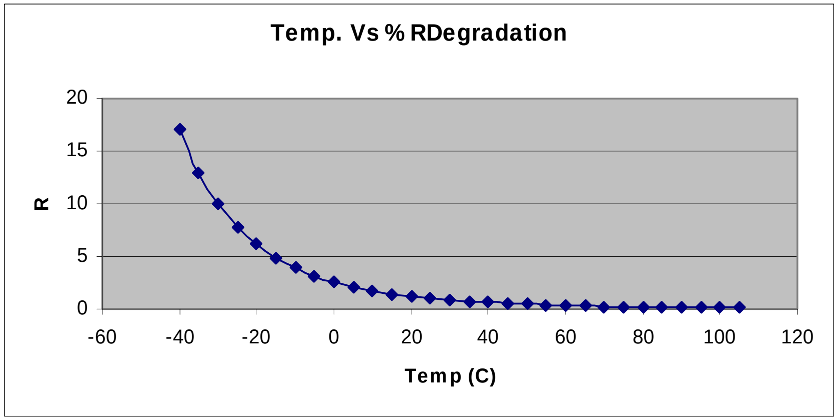
(Dallas Maxim Semiconductors, "Using Thermistors")

In order to have a linear relationship between the temperature and voltage input to the comparator, the simplest solution is to put the thermistor in a voltage divider with its series resistor (R15 in Figure 2.4) equal to the thermistor's resistance at the linearization point. In Table 2.1, the temperature coefficient (% resistance change) from the 490-2402-2-ND thermistor is multiplied by the room temperature resistance (10K) to show the resistances of the thermistor at different temperatures. The first chart plots the resistance of this thermistor against the temperature, and there is a clear exponential relationship.

To calculate the voltage that results from the voltage divider consisting of the 10K thermistor and a 10K resistor, just use

$$V_{dividier} = \left(\frac{R_{thermistor}}{R_{thermistor}+15K}\cdot 30V\right) - 15V$$

| Fahrenheit | Celsius | Tcoefficient | Resistance(O) | Vbias = 30*(Rthermistor)/(Rth. + 10K) – 15 = Voltage Input into comparator |
|---|---|---|---|---|
| -40 | -40 | 17.042 | 170420 | 13.33721317 |
| -31 | -35 | 12.993 | 129930 | 12.85607089 |
| -22 | -30 | 10.017 | 100170 | 12.27693564 |
| -13 | -25 | 7.8037 | 78037 | 11.59234186 |
| -4 | -20 | 6.1382 | 61382 | 10.79725981 |
| 5 | -15 | 4.8719 | 48719 | 9.890921167 |
| 14 | -10 | 3.8996 | 38996 | 8.877051188 |
| 23 | -5 | 3.1461 | 31461 | 7.764284508 |
| 32 | 0 | 2.5571 | 25571 | 6.566163448 |
| 41 | 5 | 2.093 | 20930 | 5.300678952 |
| 50 | 10 | 1.7245 | 17245 | 3.988805285 |
| 59 | 15 | 1.4298 | 14298 | 2.653304799 |
| 68 | 20 | 1.1924 | 11924 | 1.316365627 |
| 77 | 25 | 1 | 10000 | 0 |
| 86 | 30 | 0.8431 | 8431 | -1.27692475 |
| 95 | 35 | 0.7144 | 7144 | -2.49883341 |
| 104 | 40 | 0.6083 | 6083 | -3.65323634 |
| 113 | 45 | 0.5203 | 5203 | -4.73294744 |
| 122 | 50 | 0.447 | 4470 | -5.7325501 |
| 131 | 55 | 0.3856 | 3856 | -6.65127021 |
| 140 | 60 | 0.3339 | 3339 | -7.49044156 |
| 149 | 65 | 0.2903 | 2903 | -8.25040688 |
| 158 | 70 | 0.2533 | 2533 | -8.93680683 |
| 167 | 75 | 0.2218 | 2218 | -9.55393681 |
| 176 | 80 | 0.1948 | 1948 | -10.1088048 |
| 185 | 85 | 0.1717 | 1717 | -10.6038235 |
| 194 | 90 | 0.1518 | 1518 | -11.0461886 |
| 203 | 95 | 0.1346 | 1346 | -11.4410365 |
| 212 | 100 | 0.1196 | 1196 | -11.795284 |
| 221 | 105 | 0.1067 | 1067 | -12.1076172 |



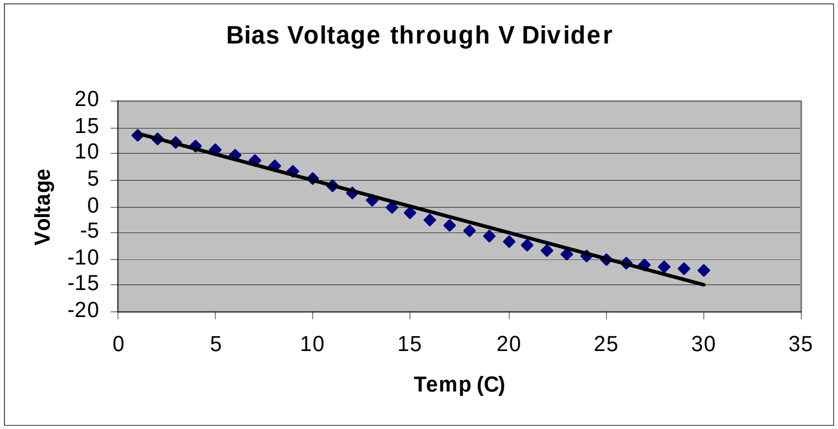




Table 2.1 The first chart graphs the resistance of the thermistor at various temperatures. The second chart graphs the voltage of the voltage of the voltage divider consisting of the thermistor and a 10K series resistor. While the resistance decays exponentially with temperature, the voltage decays linearly about the linearization point at $25^{o}$ Celsius.

This voltage is calculated in the last column of Table 2.1, and the voltage versus the temperature is represented in the second graph. The second graph shows an approximately linear relationship between the output of this voltage divider and the temperature with acceptable error for a range of temperature over 100ºC.

With this voltage, which varies linearly with the temperature, going into the temperature comparator, the temperature control system can regulate the temperature of the biodome linearly.

## Current Driver

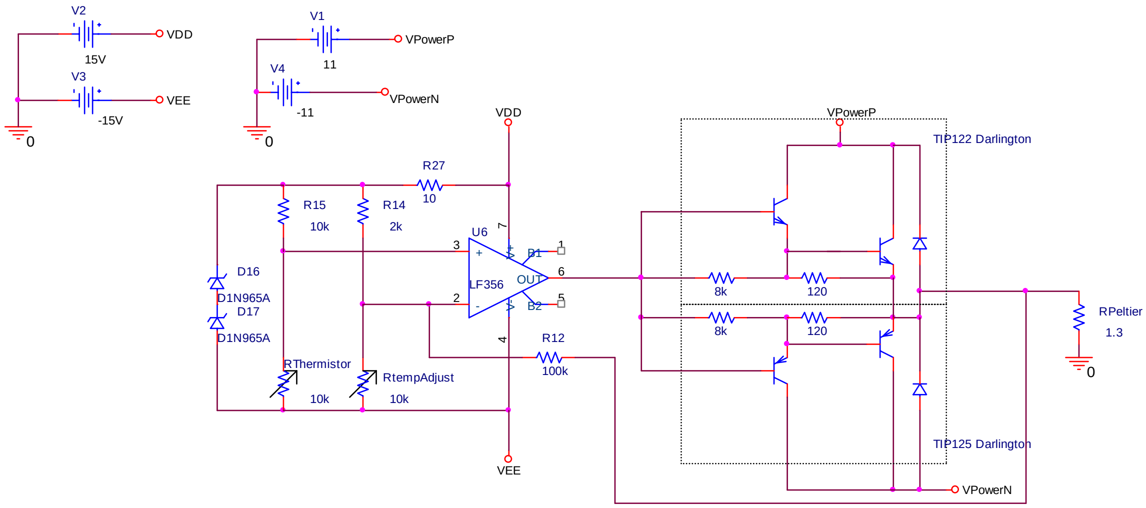



**Figure 2.4** (from previous section) Temperature Control Circuit
A 12V cooling fan, which is connected from the negative supply to ground, is not shown.

The current driver consists of a TIP122 NPN Darlington and a TIP125 PNP Darlington. In the push-pull configuration, the current gain of the driver is high while the voltage gain is slightly less than but close to 1. The Darlingtons are advertised to have a current gain of over 1000 at room temperature. The peltier device has a maximum voltage rating of 12V and at 8A. Theoretically without pull-up resistors at the base of the darlington, the opamp just has to supply 8mA for enough current to the peltier. If the opamp cannot supply enough current, then pull-up resistors could have been connected between the supplies and the output of the opamp to provide a current path from the supplies to the transistor bases.

The resistors included in the TIP122 and TIP125 darlington packages reduce the switching delay when turning off a conducting pair (for example, when the NPN is suddenly turned off and the PNP is turned on with a negative output voltage, resistors provide a voltage-dropped path from the output that will speed up the base-emitter voltage of the NPN). The diodes from the collector of the PNP connecting to the output connecting to the collector of the NPN are present to prevent back EMF spikes, often associated with applications such as motors.

The output feedback of the comparator stage comes from the output of the push-pull stage. If the output feedback came directly from the output of the comparator, there would be a range of voltages (approximately two voltage drops-corresponding to the two base-emitter junctions from the input to the push-pull to the output) for which the output is shut off. Feedback from the output of the push-pull ensures that the output voltage matches the output of the opamp. Theoretically, assuming absolute symmetry of the push-pull transistors, the only time that the output of the push-pull is zero with this configuration is if the output of the opamp is kept at zero (actual results are in the Measurements and Observations section). Two diodes also could have been inserted between the input of the push-pull and each first stage transistor base. This will cushion the input to the NPN stage by two diode drops and also drop the input to the PNP stage by two diode drops such that there is no push-pull deadzone.

The Darlington's current gain does not come without a cost. Looking at the maximum output voltage swing, the output swing is a few volts short of the supply voltages when the driving current is high. This loss of output swing at high current levels comes from the required collector-emitter drop across the transistors that is associated with increased collector current. One possible solution to this loss of output swing is to put an additional pair of NPN and PNP power transistors in parallel with the second stage of the Darlington. The current through the push-pull should be divided between the parallel pair of transistors, and the collector-emitter voltage drop of the on-transistors should be less. To prevent possible problems associated from this setup due to the different Betas in the parallel transistors, small emitter resistors could have been used to ensure equal current distribution through the parallel transistor pairs. While this seems like a good idea, especially since it reduces the heat generated in each pair of driving transistors, it is not actually implemented. Reasons for abandoning this idea are in the Measurements and Observations section.

### Power

The temperature control system is meant to be a decently precise system; therefore, the comparator should draw its power from a very-regulated supply. The 15V supplies for the comparator represent the current limited, voltage regulated control supply designed for low-power control components of the biodome. The two diodes D16 and D17, are 1N965A's (15V Zener) in series that help maintain the voltage across the comparator supply at very close to 30V. R27 is a 10Ohm resistor that works in series with the Zener diodes to regulate voltage.

The Darlington push-pull stage draws its power from the biodome's high-current and unregulated supply. Voltage ripples on the supplies from excess current draw will only change the intensity of the peltier power and should not significantly affect the feedback control of the temperature system.

### Display Driver

The LED bar graphs (see Figure 2.5) that indicate the user's input reference temperature and how hard the peltier is being driven are controlled by LM3914's (for 3914 setup, see the first section of the appendix). Essentially, the input signal must lie in the range of 0-3V, with approximately .1V corresponding to the uppermost LED that lights up on an LED bar graph display.

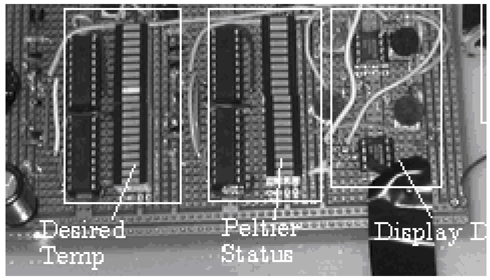



**Figure 2.5** The display LED bar graphs

The desired temperature input to the comparator can swing approximately to the 15V positive and negative power rails. An inverting adder stage can transform this signal into a 0-3V signal. The transfer equation is:

$$V_{out} = R_{feedback} \cdot \left( \frac{V_{in1}}{R_{input1}} + \frac{V_{in2}}{R_{input2}} \right)$$

$$V_{out} = R_{feedback} \cdot \left( \frac{V_{in1}}{100K} + \frac{V_{in2}}{100K} \right)$$

The input resistors (see Figure 2.6) are 100K resistors. Ideally, to scale the plus minus 15V temperature reference signal, the second input voltage should be -15V and the feedback resistor should be 1/10 of 100K. That way, the plus minus 15V signal becomes a 0 to -30V signal, and then is attenuated down to 0 to 3V. Instead of a 10K feedback resistor, a 250K potentiometer is used for flexible calibration. The second voltage input is also controlled by a voltage divider formed by a 5K and a 10K potentiometer.

A note to mention here is that the biodome's temperature reference input is a voltage that goes to the negative input of the temperature comparator. This means that as the input temperature reference voltage becomes more negative, the higher the output voltage will be and the more the biodome heats. Given this, we want the top light bar to light up at the lowest input voltage.

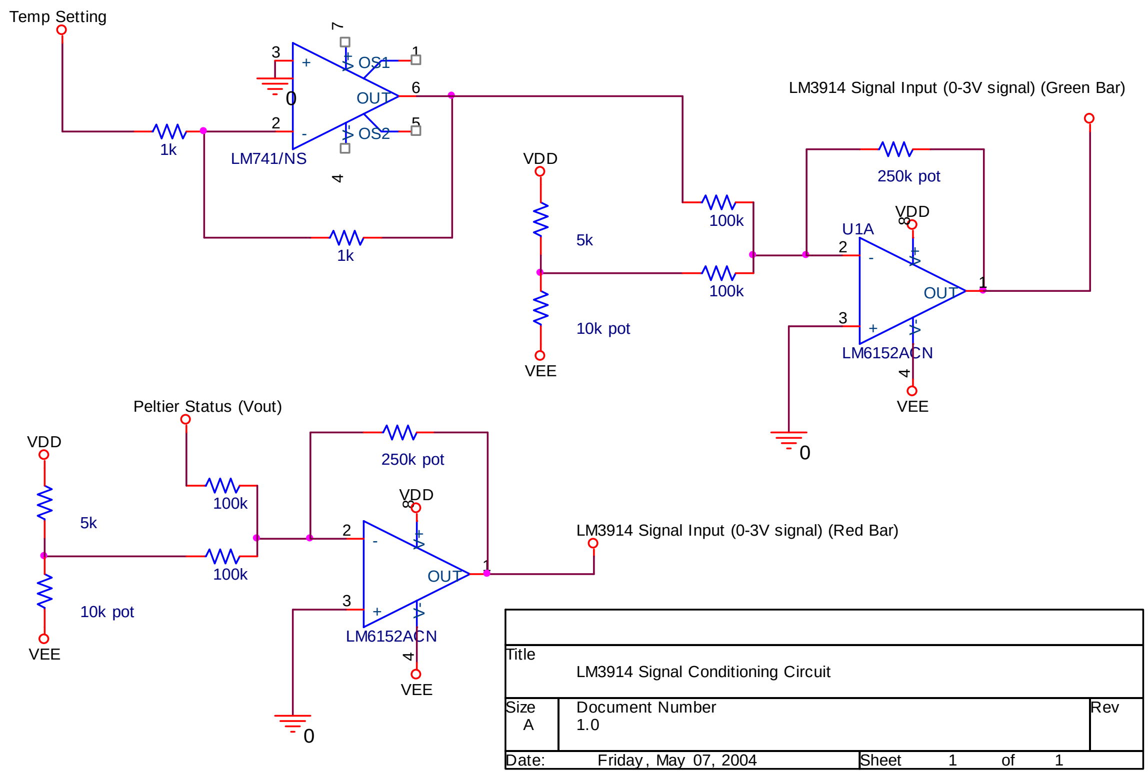



**Figure 2.6** Transformation of the Display Input Signal

To achieve this lightbar-input voltage relationship, the temperature reference signal is put through an inverter first (upper left LM741 opamp of Figure 2.6). This way, when the heater is on maximum, the input voltage is near -15V, the output of the inverter stage is +15V, and the transformed signal is ((+15-15/)10) = 0V, which corresponds to the highest bar controlled on the LM3914.

The output signal to the peltier also follows the same transformation process to the peltier status output LED bar graph. This time, however, a positive voltage indeed corresponds to an attempt at higher temperature and should light up the top LED's on the LED bar. Therefore, the output to the peltier signal is not put through an inverter first before going through the adder-scaler and then to the LED bar graph.

## 2.3 Measurements & Observations

A common question for the heating system is how extreme can the biodome's temperature be pushed. The biggest observed limit to the peltier is the heat and cold dissipation. In order for the peltier to effectively cool on one side and heat on the other side, the thermal energy from both sides must be transferred off of the peltier. In our case, transferring heat off the hot side of the peltier so that the heat does not warm the cold side was the biggest limit. The big peltier heatsink inside the biodome was more effective than the smaller peltier heatsink extending out from the biodome. Consequently, when the inside of the biodome is being heated, the big heatsink can effectively dissipate heat off the peltier. When the biodome is being cooled, however, the smaller heatsink on the outside is not as effective as the big heatsink in dissipating heat.

Our first temperature test involves leaving the biodome in a room of approximately 73ºF with both the heating and motor system activated. After fifteen minutes, the heating can reach over 100ºF, while the cooling change is extremely slow after reaching approximately 68ºF. These results are expected. The circuitry of the heating system also behaved as simulated.

## 2.4 Error Analysis

An interesting idea to increase the output power involves using parallel Darlingtons at the push-pull stage. Unfortunately without a small yet powerful emitter resistor, the variation in Beta of parallel Darlington pairs causes the Darlington with greater Beta to be turned on much more than the other Darlington. This is due to the exponential relationship between the base-emitter voltage and the collector current of transistors. More than a handful of transistors have been burned out when we first tried using parallel Darlingtons without emitter resistors. The single Darlington push-pull driver provides plenty of current room and is used in the end.

A more powerful peltier and improved heatsinks with fans should improve the output temperature swing. Both datasheets and the advertisement for peltiers the size of the biodome's peltier show ice crystals on the cold surface of the peltier, indicating that with sufficient heat dissipation and power, the peltier should be able to significantly cool down.

# 3 Light Control

## 3.1 System Overview

The objective of the light control system is to emulate the external light conditions such as sunlight. If it is bright and sunny outside, the inside of the biodome should be very well-lit. At nighttime the biodome should be dark. When clouds cover the sun, the biodome should be dimly lit.

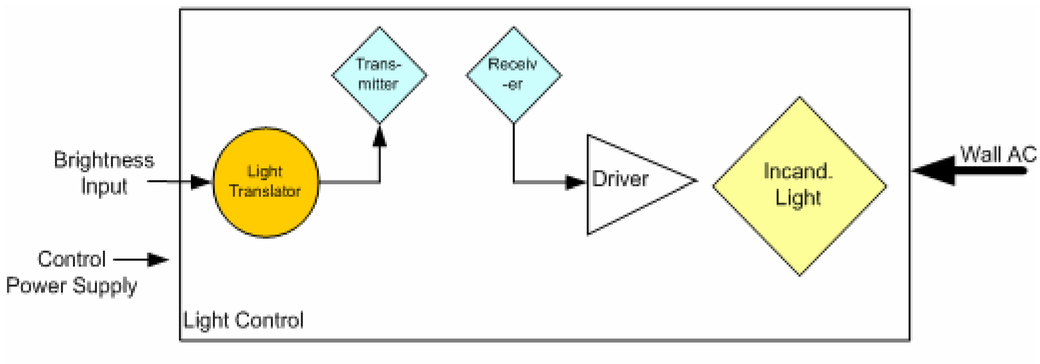



**Figure 3.1** Block diagram of the light control system.

Figure 3.1 shows the system diagram of the light control system. Some brightness input measure, such as sunlight, must be converted to a workable signal. The light input device can be placed outside so that the light detector fully receives true sunlight. The workable light-level signal is transmitted through infrared communication to the main light control at the biodome and is then used to dim or brighten an incandescent lightbulb.

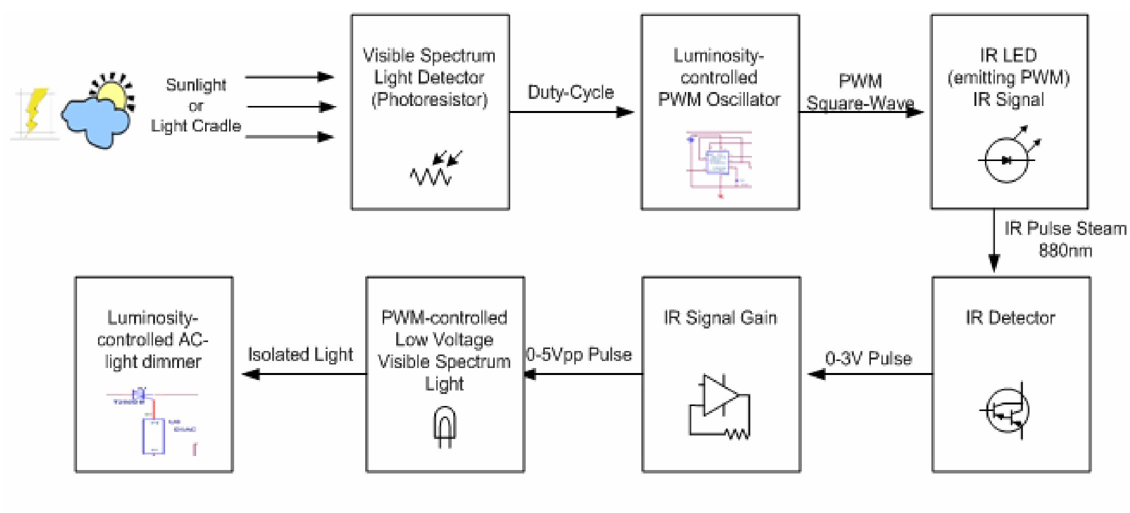



**Figure 3.2** Block diagram of the light control system.

Figure 3.2 shows the light control system in more detail. The light detector and translator, the first two boxes, is essentially a PWM controller that converts the brightness into lower duty cycle. The signal is then transmitted through powerful 880nm infrared LED's, shown in Figure 3.3.

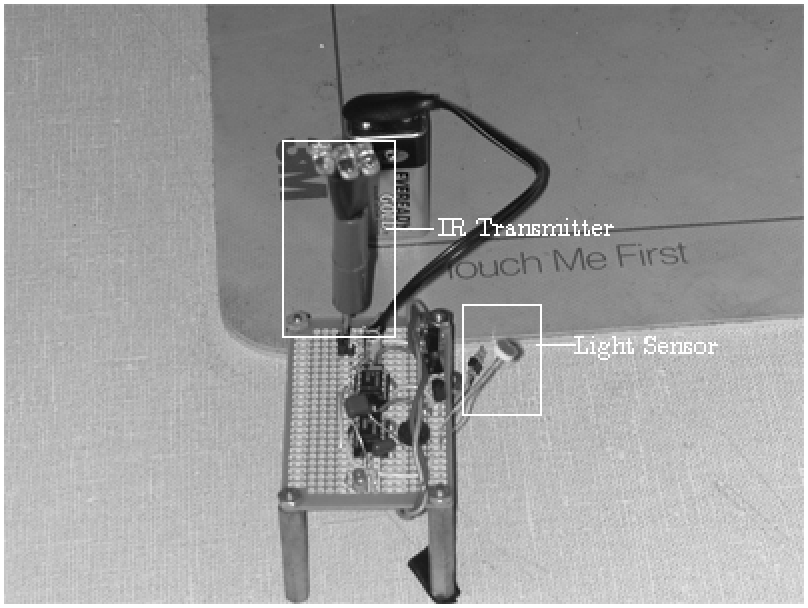



**Figure 3.3** The light detector and translator, powered by a 9V battery. The function of this device is to transmit the light intensity to the main light controller as a PWM signal.

The PWM signal, which contains the sunlight's brightness, is received by the main light controller next to the biodome (see Figure 3.4). An 880nm infrared detector captures the PWM infrared signal, which is then put through a gain stage. The purpose of the gain stage is to amplify the infrared signal, which may be greatly reduced in amplitude from long distance transmission. Filters at the gain stage are also present to clean up noise from the infrared transmission.

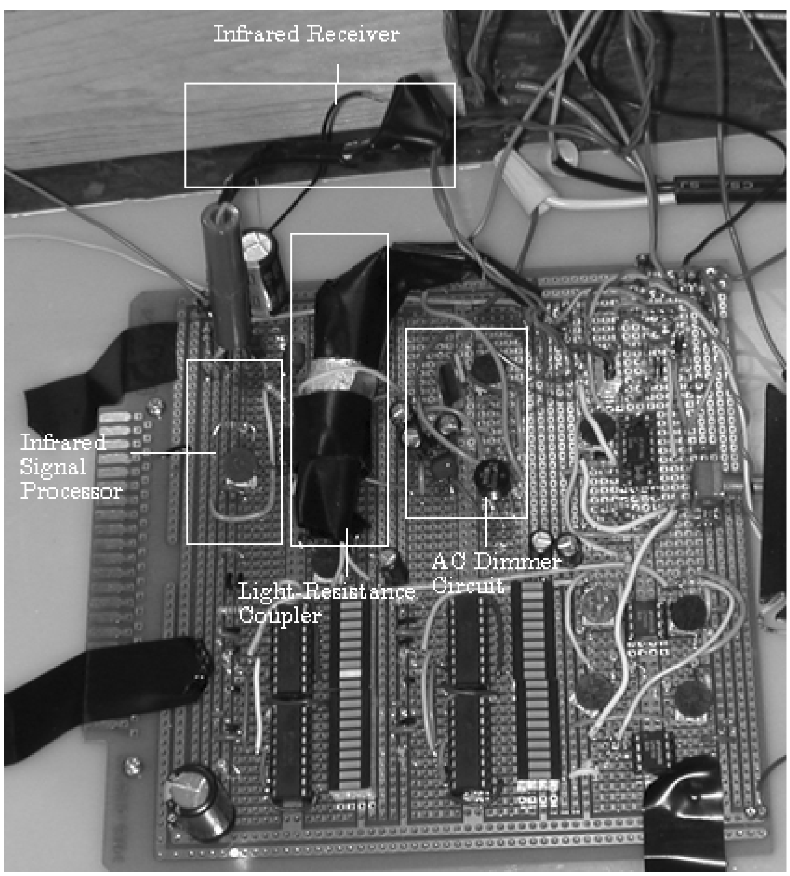



**Figure 3.4** The main light controller.

The output of the gain stage is still the PWM signal that encodes the brightness of the sunlight outside with its duty cycle. This PWM signal then drives a small lamp inside the light-resistance coupler in Figure 3.4. The reason that the PWM signal is used to drive a small light, which controls the resistance of a photoresistor, is that the AC incandescent light dimmer needs a variable resistor.

To summarize the light control system: sunlight controls duty cycle of a PWM signal. The PWM signal is transmitted via infrared communication and is then cleaned and amplified. Afterwards, the PWM signal controls a small opto-coupler, which controls the AC light dimmer. The opto-coupler consists of a PWM-driven small lamp that changes the resistance of a photoresistor. A photograph of the main light controller is shown in Figure 3.5.

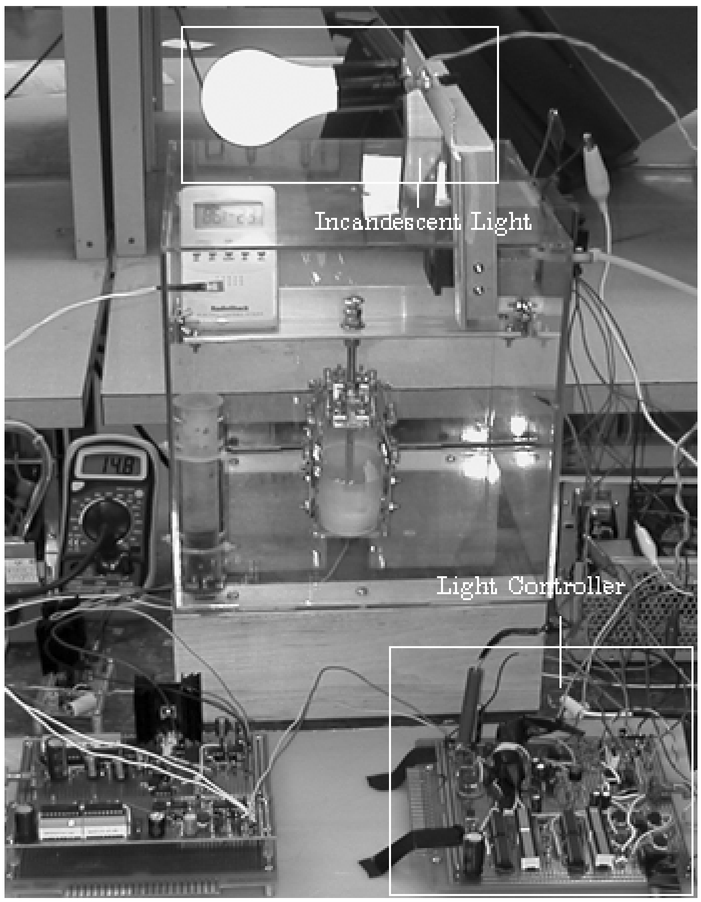



**Figure 3.5** An incandescent lightbulb is mounted onto the biodome and receives its power from the wall and main light controller.

## 3.2 Light Control Circuit

### PWM Generator and Main Light Controller

Shown on the left of Figure 3.6, the brightness to PWM translator is a 555 timer with a photoresistor controlling its duty-cycle. The duty-cycle and frequency are described by:

$$D = \frac{R_{photoresistor,111}}{R_{photoresistor,111} + R_{13}}$$

$$f = \frac{1.44}{(R_{13} + 2 \cdot R_{photoresistor,111}) \cdot C_3}$$

When the sunlight is very bright, the photoresistance decreases to less than 1K. Since $R_{13}$ is 10K and large compared to the photoresistance, the duty-cycle will approach 50%. In the absence of sunlight, the photoresistance increases to greater than 1M. When this happens, the duty-cycle approaches 100%. The frequency varies between a few hundred hertz when the photoresistance is large and a few kilohertz when the sunlight is very strong and the photoresistance is very low. Fortunately since we are interested in the time-average voltage of the PWM, choice of frequency, as long as the frequency is not too slow, is somewhat arbitrary.

The PWM signal, which encodes the sunlight brightness, is transmitted through IR LED's, represented by $D_3$, and then is received via phototransistor $Q_2$. The IR LED's are powerful QEC122's from Fairchild and the phototransistors are sensitive QSC112's also from Fairchild. The phototransistor is connected to the base of another transistor, $Q_1$, in the Darlington configuration since the strength of the infrared signal can be very weak. $R_1$ controls the voltage gain of the infrared reception stage. If $R_1$ is too large, the voltage drop across $R_1$ is too large even with noise. If $R_1$ is too small, the IR reception stage is not sensitive enough. 1K is the approximate optimal resistance that has been determined through empirical testing.

At the output of the IR receiver stage comes out a PWM signal that has the same duty-cycle as the transmitted IR signal—that is, the sunlight brightness encoding is unchanged. The signal then goes through a high-pass filter ($C_6$), which has a 3dB point at ($1/2pi*C_6R_4 = 1/2pi*.68u*50K$), which is around 5Hz. This high-pass is designed to rid some of the more slowly-varying noise without harming the PWM signal. The PWM signal can be treated as an approximate AC signal.

The PWM signal is then passed to the positive input of a LF301 opamp. The negative input is biased to roughly .1V, which is adjustable with the biasing resistors $R_{17}$ and $R_{18}$. Without any feedback, the LF301 opamp acts like a comparator and amplifies the PWM signal's amplitude to match the positive power supply.

The output of the opamp is still a PWM signal whose duty-cycle matches the duty-cycle of the original sunlight-PWM transmitter. This signal is AC-coupled through $C_7$, whose function will be revealed shortly. The PWM signal ultimately reaches transistor $Q_4$, which drives a tiny lamp $R_{19}$. $R_2$ is in series with $R_{19}$ as a current-limiting resistor so that the lamp does not burn out. It also acts as a default brightness controller. The lower $R_2$ is, the brighter the small lamp is on average. The PWM signal is fed into the base of the transistor. The time-average voltage of the PWM signal controls the time-average voltage applied to the small lamp and therefore the brightness of this lamp.

Earlier the function $C_7$ was not mentioned. The goal of the light controller thus far is to lighten or dim the tiny lamp at the end of this circuit. When the sunlight is very bright, the duty-cycle of the PWM becomes near 50%, and the voltage applied to the tiny lamp is very low. When the sunlight is very bright, the duty-cycle increases to almost 100% and the voltage applied to the tiny lamp is higher. When the IR PWM signal is not being transmitted or received, we do not want this tiny lamp to light up. When the PWM signal is filtered through $C_7$, it passes without much attenuation. When there is no PWM signal, however, the output of the opamp could potentially be pulled high. If that is the case, the AC coupling capacitor $C_7$ will not allow this high signal to pass to the lamp driver. Consequently, in the absence of an IR PWM signal, the tiny lamp remains off.

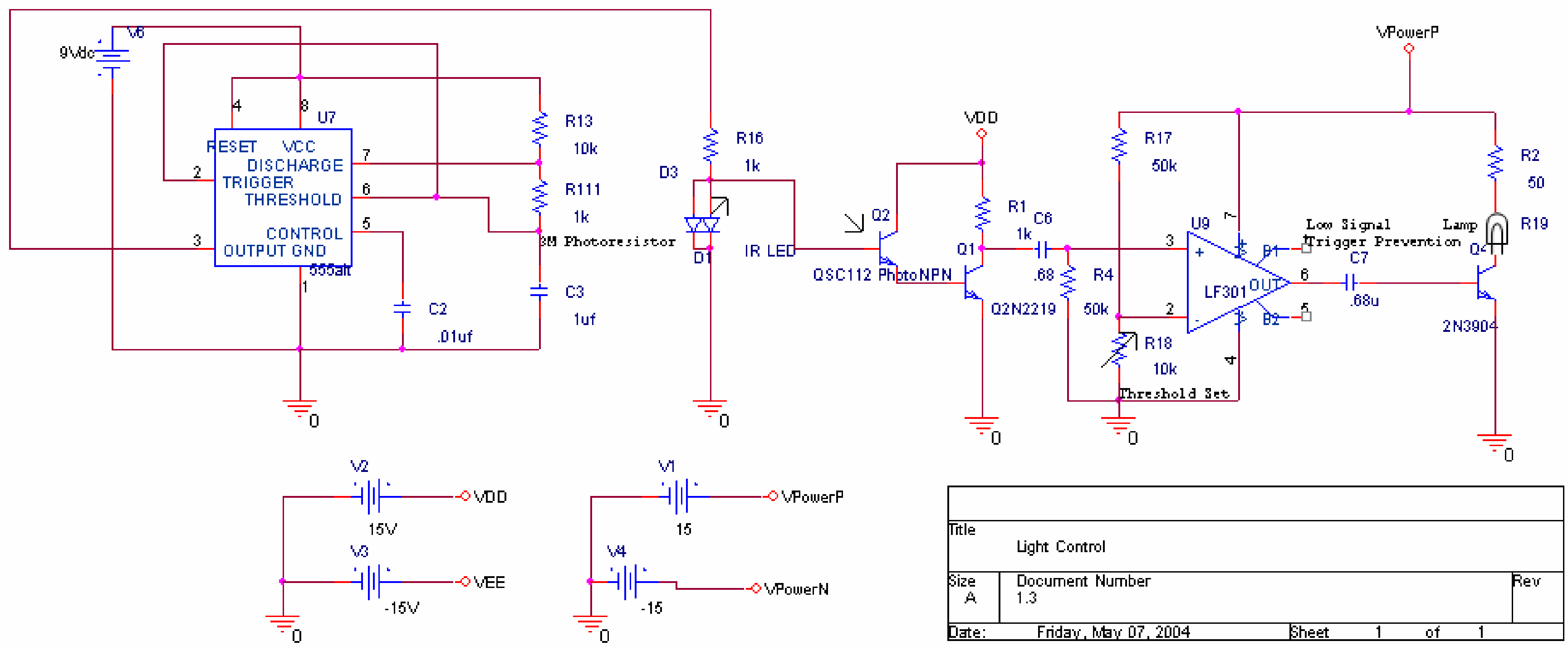



**Figure 3.6** The PWM transmitter and the main light controller circuit. Bypass capacitors (470uF to .1uF) have been placed around the circuit, especially at opamp rails, are not shown.

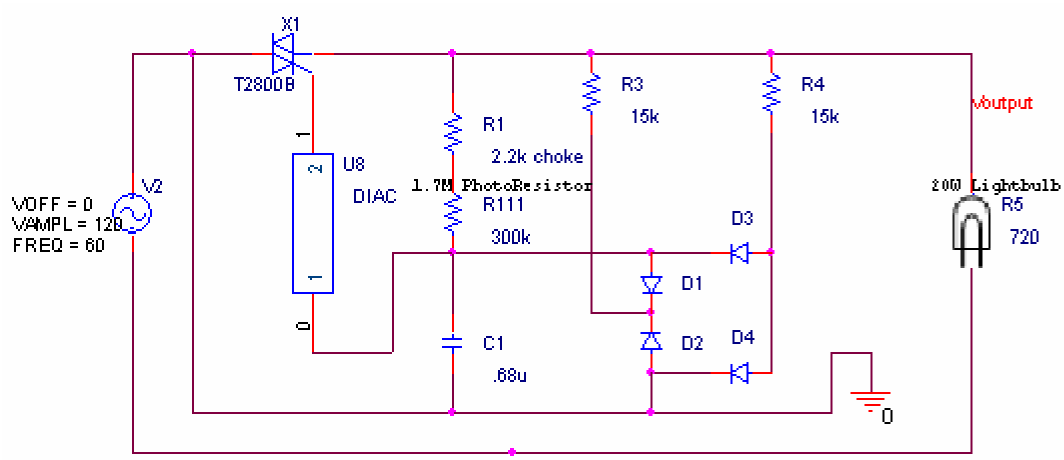



**Figure 3.7** The AC light dimmer circuit.

The AC light dimmer controls the brightness of the big incandescent lamp through the value of $R_{111}$, which is a photoresistor coupled to the tiny lamp of the main light controller. Thus, when the sun is very bright, the PWM signal's duty cycle is high, the tiny lamp is bright, $R_{111}$ becomes very low, and the big incandescent light is turned on very bright.

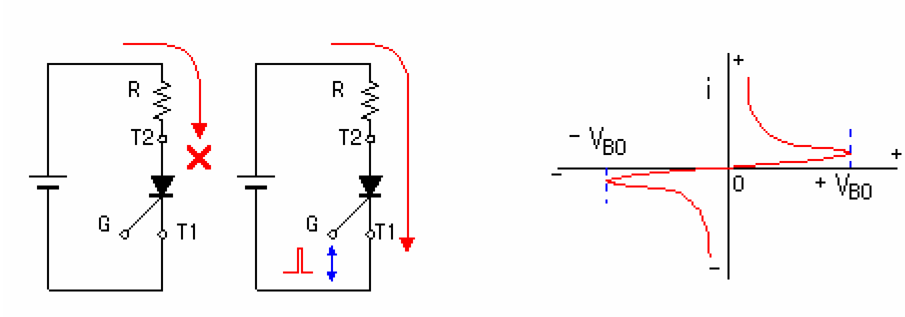



**Figure 3.8** A model of the thyristor (Triac) on the left and voltage-current time-transfer characteristics of a trigger diode (Diac)

The Triac and Diac are the key components of the AC light dimmer. Shown in figure 3.8, a Triac only allows current through its bidirectional terminals $T_1$ and $T_2$ (modeled with a diode since we are considering the forward current case) when the corresponding gate voltage and current is applied. A Diac works in conjunction with the Triac by eliminating any small voltage that can be applied to the gate of the Triac. When the voltage applied across a Diac is very low, no current conducts. When the voltage across a Diac builds up to its breakpoint, current starts conducting, and the voltage drops since the Diac starts to act like a diode (see Figure 3.8 right hand side). The 31C1428 Diac has a breakpoint voltage of approximately 30V.

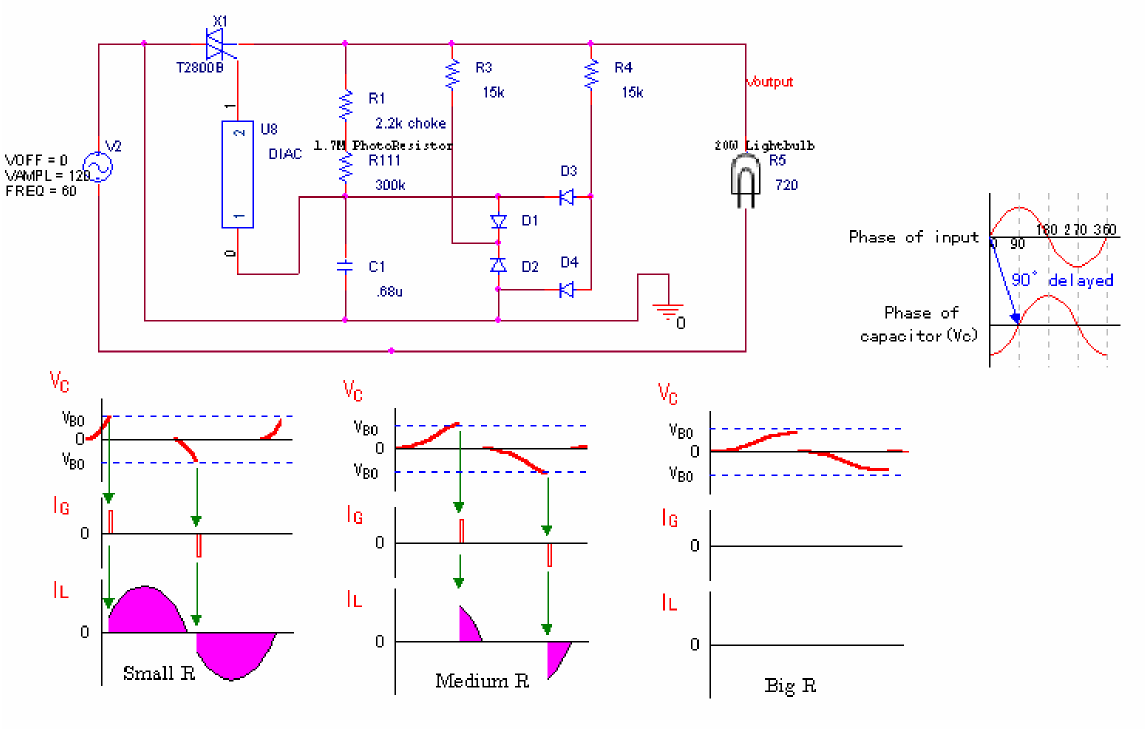



Figure 3.9 Operation of the AC light dimmer.
The AC light dimmer idea circuit is courtesy of
"The Hobby of Electronic Circuit Engineering"
http://www.interq.or.jp/japan/se-inoue/e˙ckt24.htm

The current through the Triac is limited when the gate voltage of the Triac is becomes out of phase with the diode terminal voltage (see Figure 3.9). The gate voltage of the Triac becomes out of phase through the RC series generated by $C_1$ and $R_1$ and $R_{111}$. When $R_{111}$ is large (that is, when sunlight is very dim), the gate voltage is nearing 90° delayed and little current conducts through the Triac since the gate voltage does not match the diode terminal voltages. When the sunlight is very strong and $R_{111}$ becomes small, the gate phase is very small, and current is allowed through the Triac. Note that this whole time the Diac works to limit the current to the Triac. With a first order RC network, the phase can at most be 90°. This phaseshift at the Triac gate may not be enough to current-limit the Triac, but when the Diac further suppresses this phaseshifted voltage, the gate voltage to the Triac becomes very small.

A potential problem is the failure of the capacitor to completely discharge before the next AC wave cycle arrives at the Triac. This can cause hysteric behavior, which we want to eliminate from the light dimmer. The bridge that connects to the capacitor provides and escape route for any excess charge left at the capacitor at the end of a cycle. $R_3$ and $R_4$ and $R_1$ are resistors that limit the current through the RC network and the bridge to prevent burnouts. The actual incandescent lamp is connected to one diode terminal of the Triac and one terminal of the AC line.

To summarize: the light translator at the beginning converts sunlight brightness into a PWM signal, which is transmitted, received, cleaned up, gained, and ultimately controls a small lamp. The small lamp controls the photoresistor in the AC light dimmer, which controls the phaseshift of the Triac gate voltage, which in turn controls the brightness of the incandescent light.

## 3.3 Observations and Measurements

The wonderful thing about the light controller is that the output is obvious when the circuits are working correctly. By adjusting the voltage gain of the main controller's tiny lamp through $R_2$, the sensitivity of the AC light can be brought to extremes. At one extreme, the incandescent light simply will not turn off. At the other extreme, the incandescent light only turns off when there is absolute darkness.

By adjusting $R_1$ and the capacitor of the AC light dimmer circuit, the average brightness of the incandescent light at a fixed input PWM signal can be adjusted. This is due to these two components' altering the phaseshift of the AC light dimmer circuit.

Overall, the lighting control circuit is a very flexible circuit. The range of the IR transmission exceeded 10 feet. If stronger or more diffusive IR LED's and phototransistors are used, this range can be dramatically increased.

Indeed, with the biodome's demonstration setup, when a flashlight is shined upon the sunlight detector, the biodome's incandescent light shines brightly. When the sunlight detector is covered in darkness, the biodome's light is turned off. With the light level in the sixth floor laboratory, the biodome's light is turned on to a soft orange.

## 3.4 Error Analysis

One problem that occurred with the light control circuit is that the biodome's Incandescent lightbulb triggered the phototransistor that is supposed to receive the PWM signal. When the lightbulb is turned slightly on, its light emission forces current through the phototransistor, which in turn drives the output of the PWM reception stage down. This causes the next stage to think that there the PWM duty cycle is 0%, which turns off the incandescent light and stops the interference. When this happens, the PWM signal is transmitted successfully again and the incandescent light turns on. Once again, the incandescent light's own emission starts to interfere with the IR transmission, and an incandescent light's brightness oscillation at about 1Hz is very noticeable.

The quick solution for this is a small electrical tape cover on top of the phototransistor, which blocks any emission from the incandescent light to the phototransistor. A more permanent solution may involve filters to filter out the incandescent light signal or a band-pass filter for the PWM signal.

# 4 Humidity Generation and Control

## 4.1 System Overview

In its entirety, the humidity generation and control system allows the user to view the current humidity level within the control environment and add more water vapor to the air if desired. The humidity sensor, or hygrometer, is connected to measurement circuitry that turns the humidity level into a voltage which can then be shown on an LED display. On the other hand, humidification is accomplished ultrasonically by vibrating water at high frequencies to form a standing wave that eventually break the surface of the water and converts it into a mist. This method is chosen over heating the water since temperature control is another monitored environmental element and adding more thermal energy would make obtaining lower temperatures very difficult.

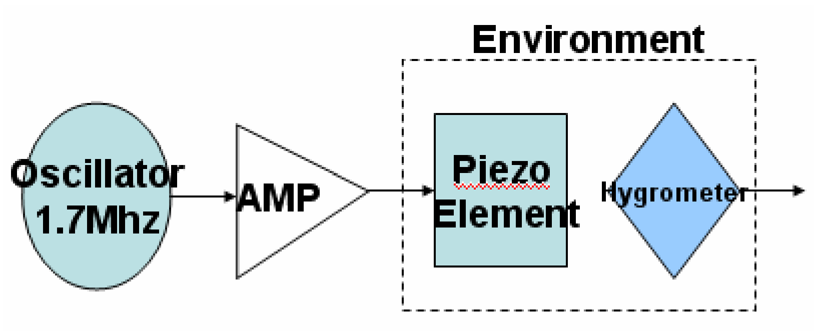



**Figure 4.1** Block Digram of the Ultrasonic Humidifier

## 4.2 Circuit Explanation

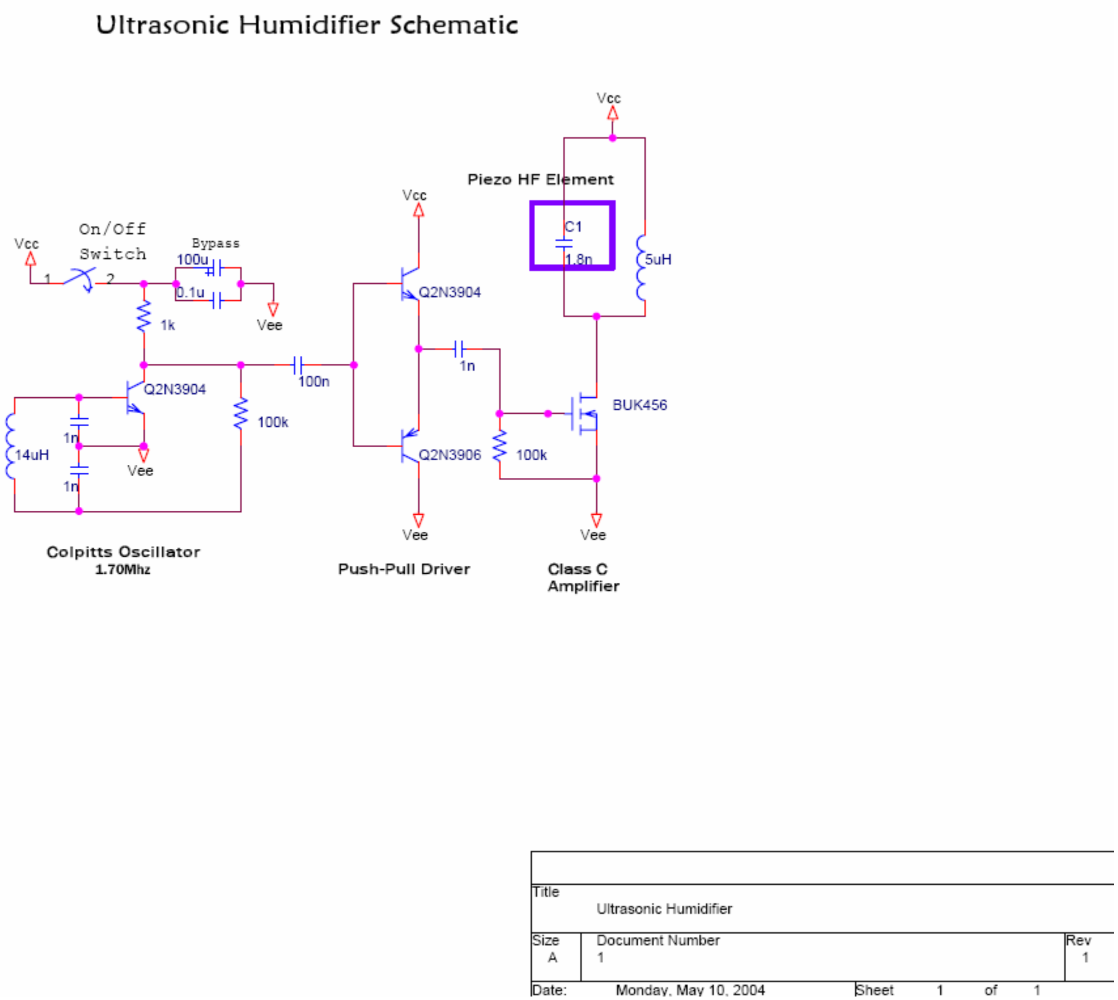



Figure 4.2 Ultrasonic Humidifier Schematic

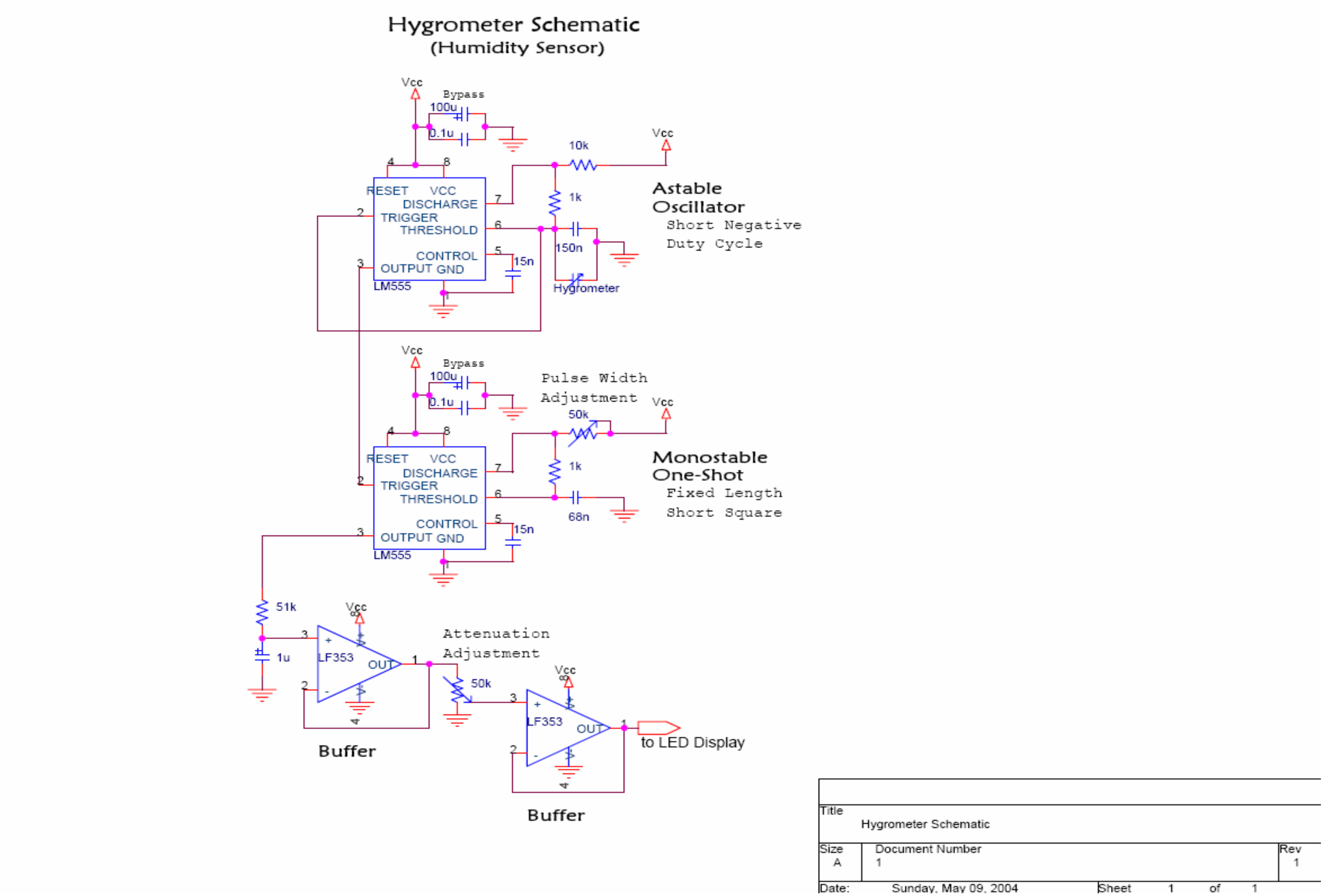



Figure 4.3 Hygrometer Schematic

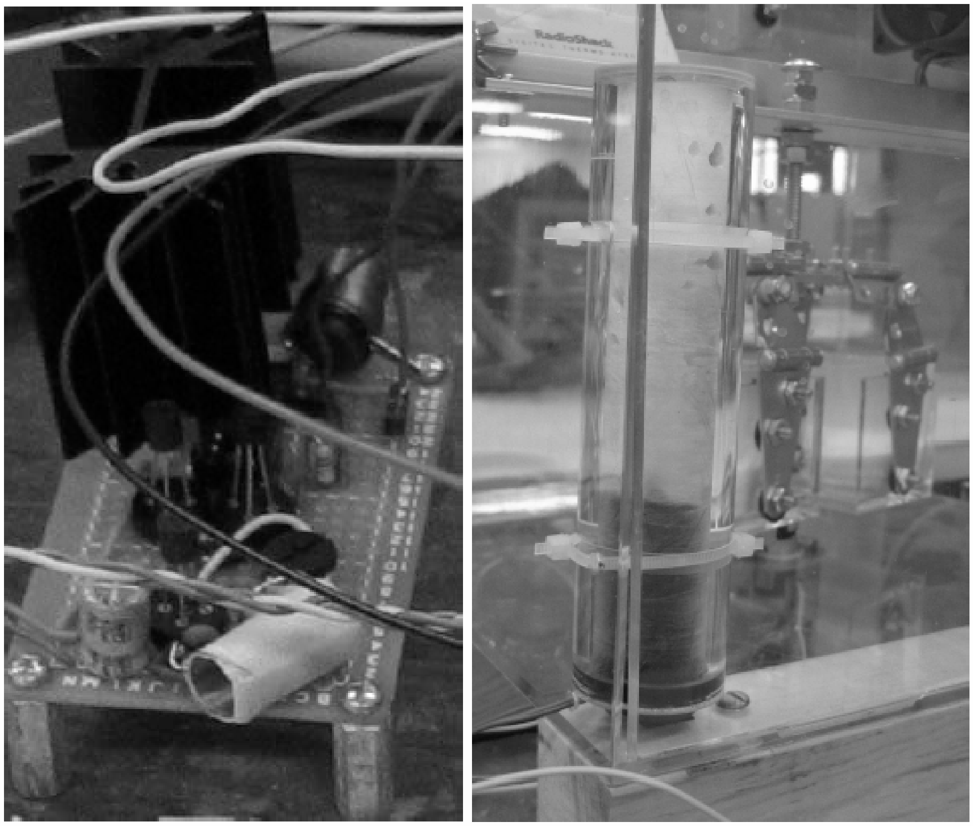


Figure 4.4 The left photograph shows the ultrasonic humidifier driver circuit. The right photograph shows the column of water to be vaporized.

### Ultrasonic Humidifier

The ultrasonic humidifier starts out with a 1.7MHz oscillator. To accomplish this, a colpitts configuration was used. Assuming that the transistor is off at power-on, the 1k pull up resistor will force the output to go high. This is fed back via a 100k resistor to a tuned LC tank at 1.7Mhz. However, when the voltage rises far enough to turn the transistor on, the output is pulled low, which in turn sinks current from the LC pair and pulls the input voltage to the base of the transistor down. This prohibits current to flow into the collector and brings the circuit back to the beginning of the cycle. There is one exception, though. The long-run behavior (many cycles after power-on) of the oscillator improves as stored energy in the inductor and the capacitor is sloshed back and forth at resonance and behaves much more consistently than the first dozen cycles.

The oscillator behaves very well, but cannot drive much current at the output. It is for this reason that a transistor pair push-pull is used to buffer the oscillator voltage and allow for substantial current gain to drive the MOSFET. A biasing network was considered, but not implemented since a pure sine wave is not necessary and the added components seemed to outweigh the loss of $\pm .6$ volts in the prototyping phase.

The final stage of the oscillator is a high voltage, high current class C amplifier. Since the inductor and capacitor above the MOSFET are in parallel, they form a nice resonant point and allow for a peak-to-peak voltage of well over 70 Volts. This is very important since the piezo element needs a peak-to-peak voltage of at least 65 Volts to cause the water droplets at the top of the standing wave to escape into a vapor. The MOSFET essentially gives the resonant piezo/inductor pair a kick at the frequency of the input which, in this case, is 1.7Mhz. Even though the class C amplifier is designed to give a sinusoid at twice the input voltage at the output of the resonant device, if the device is slightly out of resonance, a higher voltage, non-sinusoidal signal can be generated. This can be quite beneficial when a large peak-to-peak voltage is needed.

Since voltages at the output can reach over 150 Volts peak-to-peak at startup, a high voltage MOSFET was used. While a BJT could have been used here instead, initial trials pushed them beyond their maximum ratings at startup and caused them to not work properly. The BUK456 MOSFET did not have these problems and handled even the harshest power-on transients beautifully.

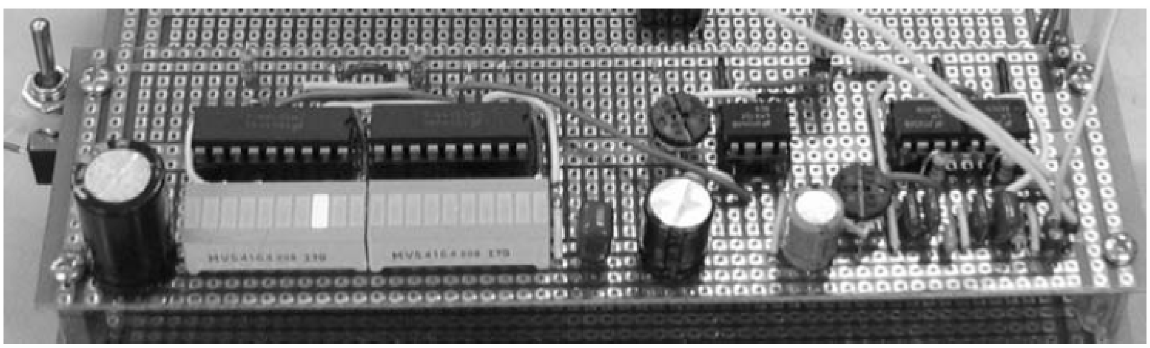


**Figure 4.5** The hygrometer circuit.

**Hygrometer**

The humidity sensor circuitry can be broken down into three basic stages. The first stage is a variable frequency inverted pulse train. In other words, a square wave with a duty cycle much greater than 50% is generated. The capacitance, which is comprised of the addition of a 150nF capacitor and the hygrometer, is charged via a 10k and a 1k resistor and is discharged through the 1k resistor only. This means that the rising time constant (RC) is eleven times larger than the falling time constant, thus producing a duty cycle of roughly 11/12 or 0.92. The frequency of the output depends on how long it takes to discharge and charge the capacitors. Since the capacitance value of the hygrometer changes with humidity, the output frequency will change as well.

The second stage is a fixed width, one-shot square wave. When driven by the high duty cycle signal from the previous stage, a fixed length pulse is produced on every rising edge as the 68nF capacitor is charged through a 1k resistor and a 50k potentiometer. If the input period is very close to the pulse width, the average output waveform voltage will be very close to the positive supply. Contrary wise, if the input period is much larger than the fixed pulse width, the average output voltage will be very close to zero. The combination of the two LM555 timers in the above configuration creates a pulse width modulator (PWM) in which the duty cycle of the output waveform is proportional to the input capacitance of the hygrometer.

Finally, the pulse width modulated signal is passed through a low pass filter and scaled to drive the LED display correctly. The low pass filter was chosen to create a near-constant voltage across the capacitor at the input PWM frequency. (approx. 1kHz)

$$f_{3dB} = \frac{1}{2\pi RC} = \frac{1}{2\pi(51k\Omega)\cdot(1\mu F)} = 3.12Hz << 1kHz$$

The signal is then put through a buffer so that the voltage across the capacitor is not significantly altered by a load and the true low-passed value can be used. A variable voltage divider is used at the output to correctly scale the voltage for the LED display. This new value is then once again buffered to supply the current needed by the display circuitry.

## 4.3 Measurements & Observations

The hygrometer is a humidity sensing element that changes capacitance depending on the level of moisture in the air. The approximate range of capacitance values were measured to be 0.1nF ˜ 0.4uF.

Calculating the Frequency range of the short negative duty cycle astable oscillator:

$$f = \frac{1}{0.693\cdot(R_1 + 2R_2)\cdot C} = \frac{1}{0.693\cdot(10k\Omega + 2\cdot 1k\Omega)\cdot(150nF + C_{hygro})}$$

$$C_{low} = 0.1nF : f_{high} = 801.1Hz$$

$$C_{high} = 0.4uF : f_{low} = 218.6Hz$$

Calculating the range of achievable positive durations for the monostable one-shot timer.

$$t_{high} = 0.693\cdot(R_1 + R_2)\cdot C = 0.693\cdot(R_{50K\_POT} + 1k\Omega)\cdot 68nF$$

$$R_{50K\_POT} = 0\Omega : t_{high\_MIN} = 47.1\mu\sec$$

$$R_{50K\_POT} = 50k\Omega : t_{high\_MAX} = 2.40m\sec$$

$$t_{high} \approx 0.9 \cdot \frac{1}{f_{high}} = 0.9 \cdot \frac{1}{801.1Hz} = 1.12m\sec$$

$$t_{high\_MIN} < t_{high} < t_{high\_MAX}$$

$$47.1\mu\sec < 1.12m\sec < 2.40m\sec$$

The desired positive duration can be achieved by adjusting the $50k\Omega$ potentiometer to $22.8k\Omega$.

All systems worked very well when they were built and tested and needed only a small amount of adjusting via the positive duration pulse-width-adjustment potentiometer.

## 4.4 Error Analysis

Since the hygrometer was pulled out of a commercial humidity meter, extensive datasheets and device characteristics were not available. The capacitance and resistance were measured as the humidity level around the sensor was changed. The dominant property that changed was the capacitance, and since most hygrometers are based upon measuring the capacitance of the sensor, a capacitance to voltage circuit was created. However, it seems that the output voltage is actually a logarithmic function of the humidity. Therefore the LED display remained somewhat constant unless the humidity level was changed substantially.

A solution to displaying the logarithmic nature of the hygrometer would be to use a logarithmic amplifier before the signal is sent to the LED display. This could have an adjustable potentiometer for dialing in the correct voltage level to send to the display. Another possible solution would be to use a pair of LM3915's (logarithmic bar/dot display driver) instead of the LM3914's (linear bar/dot display driver). This would require a few different resistor values in the 20 segment display circuit, but would probably perform very nicely without much re-design.

A small problem was also encountered regarding the ultrasonic humidifier and the supply voltage it receives. To generate a noticeable mist, the supply voltage to the humidifier needs to be greater than $\pm 15.5$ Volts. Without other loads on the high current power supply, this is not a problem. But when other high current loads, such as the heating/cooling peltier and the motor, pull on the supply, the average voltage can dip as low as $\pm 12$ Volts. This produces nothing more than a sputtering of water without the desired mist. A simple solution would be to use a higher voltage power supply. At $\pm 20$V the mist is quite impressive and most likely worth the extra cost of a separate transformer.

# 5 Gravity Generation and Control

## 5.1 System Overview

The goal of the gravity generation and control system is to spin a symmetrical arm with two environmental "baskets" such that the resultant acceleration, normal to the basket, essentially creates the effect of an amplified gravitational environment. The user will be able to set a desired "gravity level" and the system should slowly track to that level to minimize angular acceleration which could perturb the test baskets. Finally, a display shall be made to show the user the current angular velocity of the motor and also the reference level that the system is slowly achieving.

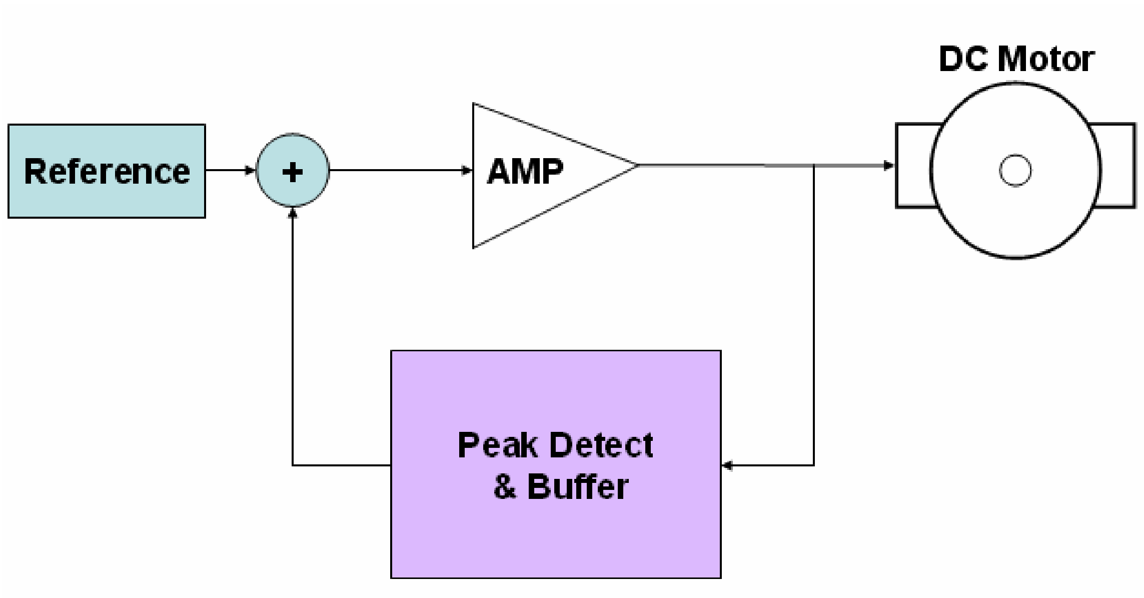



Figure 5.1 Block Diagram of the motor and gravity control.

## 5.2 Circuit Explanation

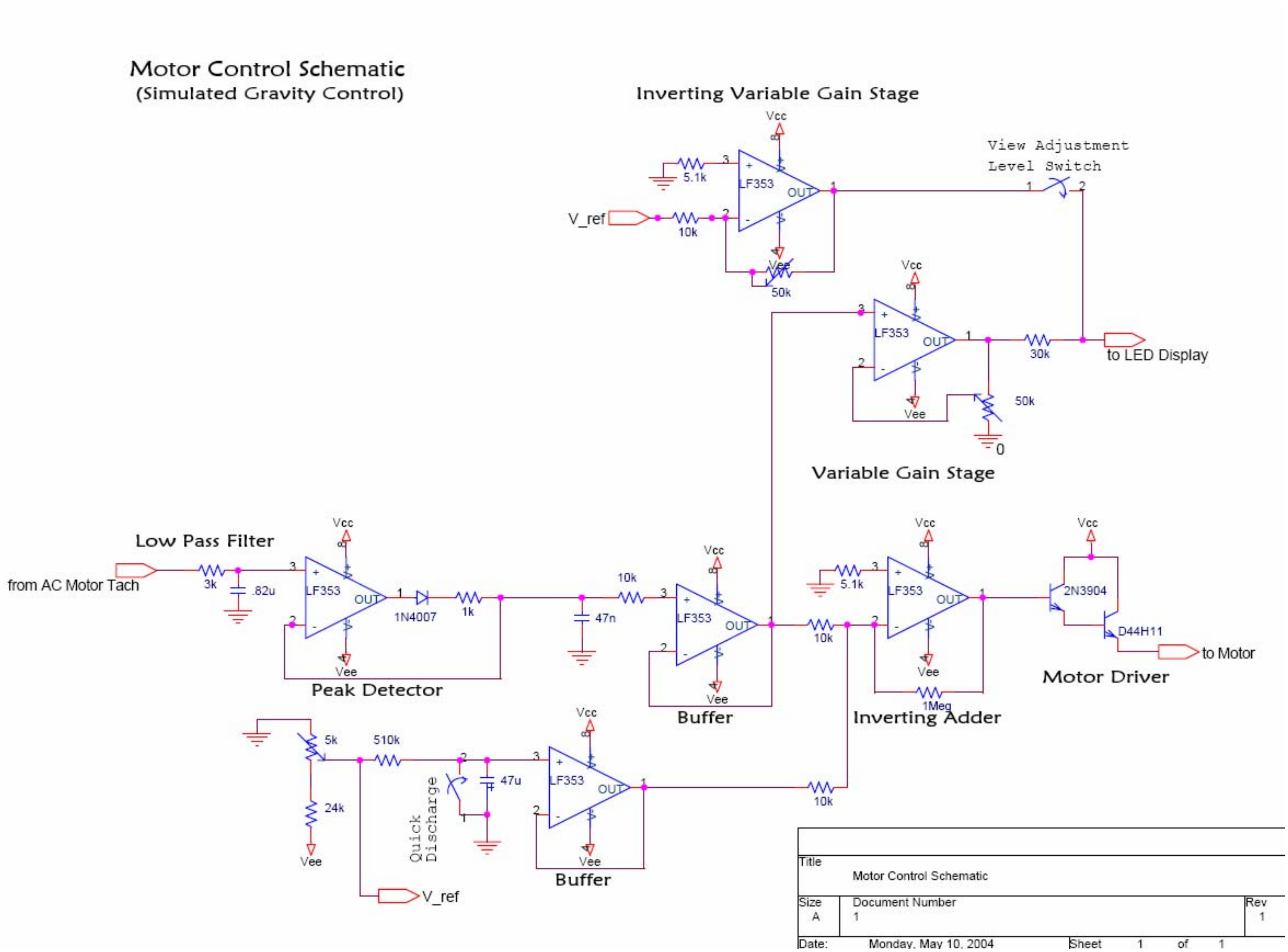



**Figure 5.2** Motor Control schematic.
Bypass capacitors (470uF to .1uF) have been placed around the circuit, especially at opamp rails, are not shown.

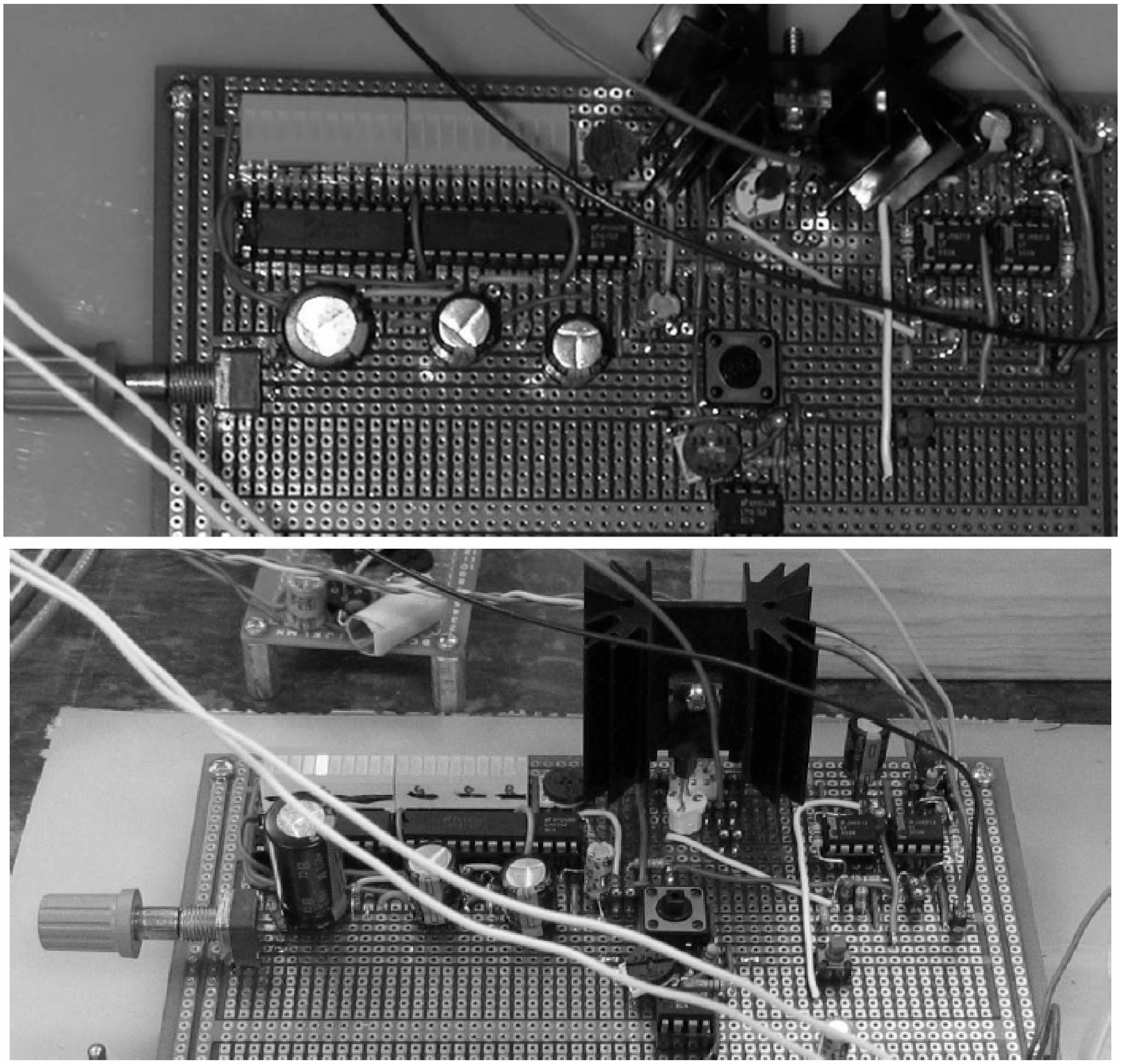


**Figure 5.3** Motor Control circuit (bird's eye view and side view).

I will start the analysis of this circuit at the input from the tachometer. (from AC Motor Tach) To reduce high frequency spikes that can result from the primary motor being close to the AC generator (AC tachometer), a low pass filter is used. The pole of the filter is placed high enough such that the desired AC signal is not greatly attenuated (no more than 20 revolutions per second) and low enough to greatly diminish high frequency voltage spikes.

$$f_{3dB} = \frac{1}{2\pi RC} = \frac{1}{2\pi(3k\Omega)(0.82uF)} = 65Hz$$

The filtered signal then goes through a peak-detector OpAmp circuit. The 1k resistor enclosed in the feedback path keeps the OpAmp from every needing to limit its output current. Since almost no current enters the LF353 at its inputs, the only method of discharging the peak-holding capacitor is through the reverse-biased diode. It is for this reason that a diode with a somewhat large reverse leakage current (1N4007 ~ 5uAmps) was selected.

The peak-detected DC signal goes through a buffer so that the 47nF peak-holding capacitor is not drastically altered by other circuits that use its voltage level. One of those circuits is a non-inverting variable gain stage used to drive the LED display with the correct voltage range. The gain ranges from 1 to the gain limit of the OpAmp, however only a factor of about 2 is needed for this application.

Below the peak detector is the input voltage reference level. The resistor divider values were chosen to limit the user's input range and also give the user greater resolution in the practical range when trying to dial in a desired angular velocity. The output of this voltage divider goes through a 510k resistor and then to a large 47uF cap to create long and smooth transitions between the desired value and the value that the feedback system is comparing.

$$\tau = RC = (510k\Omega)(47uF) = 24.0 \text{ seconds}$$

A switch is placed in parallel with the reference capacitor to allow for a quick stop in case of failure or oscillations. The reference voltage on the capacitor is sent through a buffer and then fed to an inverting adder to find the difference between the current peak-tachometer-voltage and the reference voltage. The difference is gained by 100 and sent to a darlington NPN transistor pair to drive the motor.

The reference voltage at the input potentiometer is also sent through an inverting variable gain stage (as shown at the top of the schematic) which can be seen on the LED display for easy adjustment. To do this, a momentary switch at the output of the inverting gain stage can be pressed, overpowering the 30k resistor from the peak-detected output, and thus showing the current reference voltage.

Since the motor can require up to 1Amp to function correctly, the high current power supply at approximately $\pm 16$V was used for Vcc and Vee. Eventually it was decided that Vee should come from a cleaner lower-current supply since the load on the negative rail for the motor control is minimal.

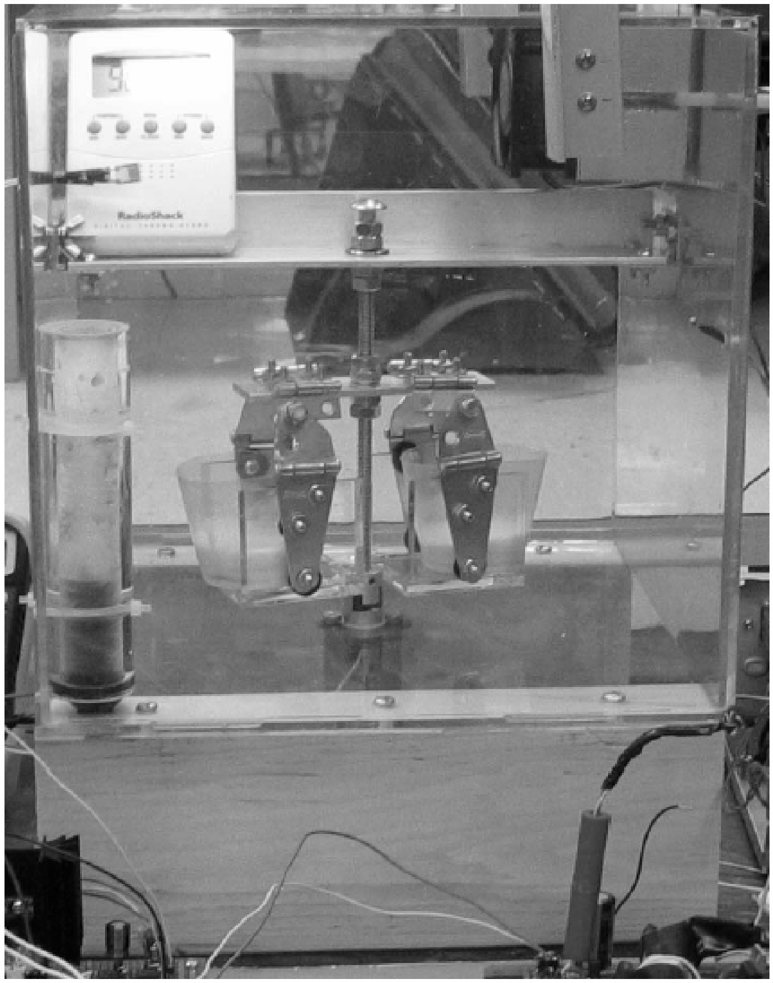



Figure 5.4 Baskets are attached to the motor shaft in the biodome.

## 5.3 Measurements & Observations

Finding the maximum acceleration (simulated gravity):

Measured Maximum DC converted
Tachometer Voltage (peak detector):

$$V_{tach\,MAX\_DC} = 1.75 Volts$$

2.0 Vrms = 1000 Revolutions/Minute (RPM)

$$V_{tach(peak-to-peak)MAX} = 2 \cdot V_{tachMAX\_DC} = 2 \cdot (1.75) = 3.50 Volts$$

$$V_{tachMAX\_RMS} = \frac{V_{tach(peak-to-peak)MAX}}{2 \cdot \sqrt{2}} = \frac{3.50}{2\sqrt{2}} = 1.237 Vrms$$

$$RPM_{MAX} = \frac{V_{tachMAX\_RMS}}{2.0 Vrms} \cdot 1000 = \frac{1.237}{2.0} \cdot 1000 = 618.5 RPM$$

$$\omega = \frac{RPM \cdot 2\pi}{60} = \frac{(618.5) \cdot 2\pi}{60} = 64.8 rad/\sec$$

$$a_{\tan} = \frac{(v_{\tan})^2}{radius} = \frac{(\omega \cdot radius)^2}{radius} = \omega^2 \cdot radius$$

Assuming environment basket is perfectly horizontal @ high speed.

$$radius = 10cm = 0.1m$$

$$a_{\tan} = \omega^2 \cdot radius = (64.8)^2 \cdot (0.1) = 419.9 meters/\sec^2$$

$$a_{gravity} = 9.81 meters/\sec^2$$

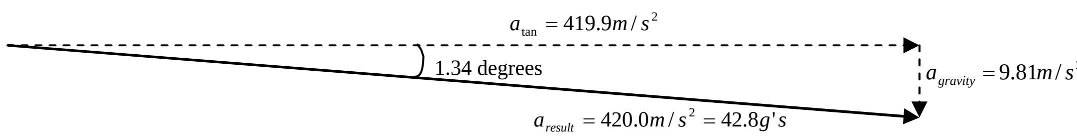
$$a_{result} = \sqrt{(a_{gravity})^2 + (a_{\tan})^2} = \sqrt{(9.81)^2 + (419.9)^2} = 420.0 meters/\sec^2$$

Conversion to g's:

$$g's = \frac{a}{a_{gravity}} = \frac{420.0}{9.81} = 42.8 g's$$

Is horizontal approximation good?

$$\tan^{-1}\left(\frac{9.81}{420.0}\right) = 1.34^\circ \text{ from horizontal (great!)}$$




## 5.4 Error Analysis

At very low speeds the system does not behave ideally because the peak-detected AC tachometer voltage falls off between peaks even though the motor is turning at a constant velocity. This confuses the feedback control into thinking that more power should be applied to the motor to bring its angular velocity back to the desired reference value. The result is a slow stop-and-go motion as the reference level approaches, but has not yet reached, a value of zero volts.

To remedy this unfortunate side effect of the AC tachometer, a switch was installed to quickly discharge the reference capacitor that can be pushed when the device reaches very slow speeds. This worked out very well since the inertia is substantial enough to allow for a slow and smooth stop.

Another important error that was discovered involved the choice of power supplies to drive and control the motor. The system manages to perform very well with a noisy positive supply, but runs unacceptably with a noisy negative supply. This is because the reference voltage is based upon a voltage divider between the negative power supply and ground and can confuse the user when looking at the reference value on the LED display. Therefore, instead of using the high-current power supply for both the positive and negative voltage sources, using it only for the positive source and using the cleaner, lower-current supply for the negative supply rail proved to be a very good solution.

# 6 Power Supplies

## 6.1 Control Power Supply

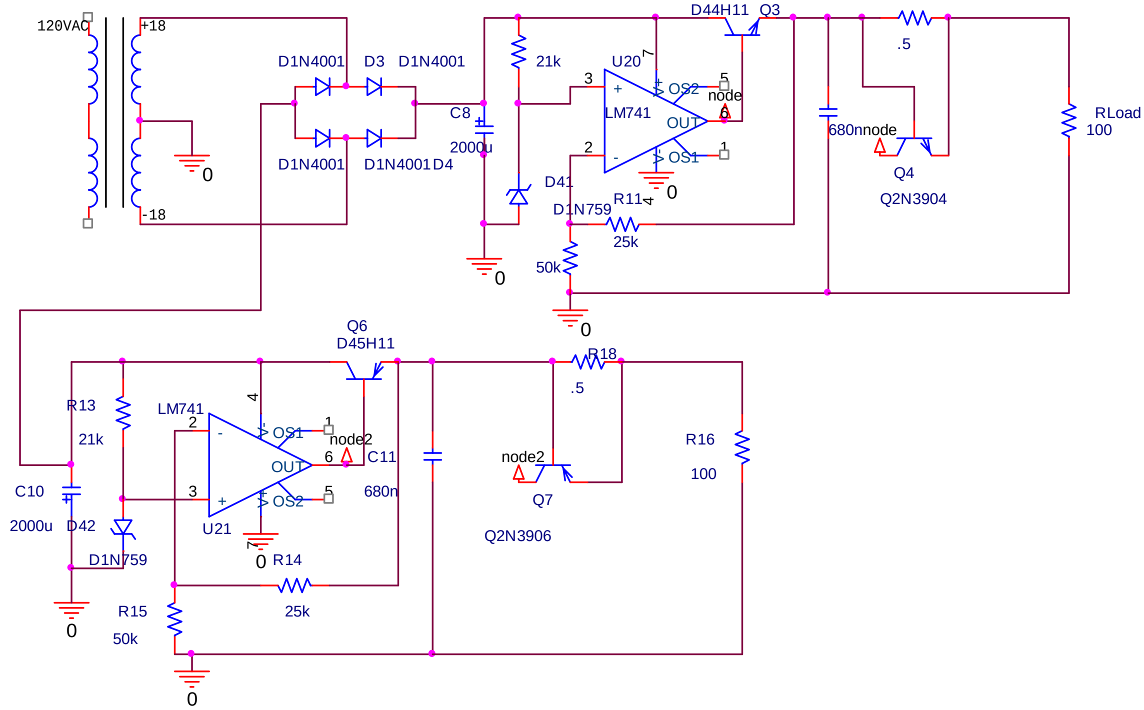



Figure 6.1 The Control Power Supply Circuit
Red and green LED power indicators in series with a 5K resistor from the positive and negative outputs and a cooling fan are not shown.

The control power supply is a plus and minus 15V supply used mainly for the opamps (see Figure 6.1). The transformer used was a 36V transformer. A bridge rectifier is used for maximum output voltage. In order to reduce the ripple at the output, large 2000uF capacitors are used at the end of the bridge circuit. The Zener diodes $D_{41}$and $D_{42}$ are 1N759 Zener diodes that regulate to 15V. When the Zener reference voltage is connected to the input of an opamp (LM741), adjusting the gain of the opamp with the feedback resistor ($R_{25}$and $R_{14}$) allowed the output voltage swing up to positive and negative 25V (the output of the transformer with no load exceeded the advertised 36V).

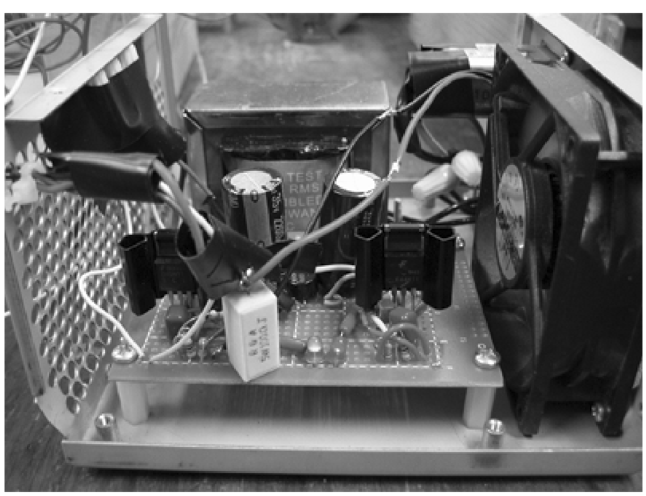


Figure 6.2 The Control Power Supply encased in a metal box with a fan.

The outputs of the opamps connect to the bases of power transistors $Q_6$ and $Q_3$, which are the D4XH11 series transistors. The emitters of these transistors then are connected to the base of a 3904 for the positive output and a 3906 for the negative output. The 390X transistors act as current limiters. The .5Ohm resistor in connecting the base of the 390X transistors to their emitters will allow roughly 1.2A of current before the base-emitter voltage of the 390X transistors is high enough for the 390X transistors to turn on and take all of the current from the opamps. When the current from the opamps are rerouted through the 390X transistor, there is little current left for the big D4XH11 transistor, and the power supply will not allow any more current to pass through. Thus the power supply is limited to 1.2A (see Figure 6.2).

## 6.2 High Current Power Supply

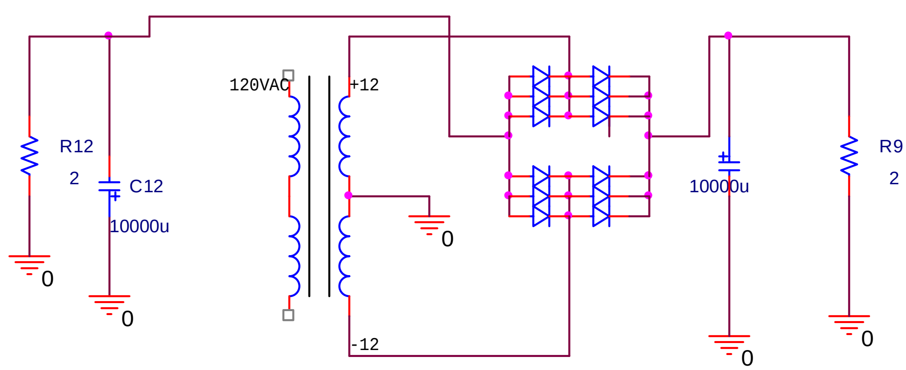



**Figure 6.3** The High Current Power Supply Circuit
$R_9$ and $R_{12}$ are loads that model the peltier and the motor for the biodome.
The bridge diodes are in parallel to model a high-current bridge rectifier.
Red and green LED power indicators in series with a 5K resistor from the positive and negative outputs and a cooling fan are not shown.

The high current power supply is a dubbed-down version of the control power supply (see Figure 6.3). There is no voltage-controlling opamp and Zener diode combination, and there is no current-limiting transistor at the output. We want to achieve the maximum output voltage possible to provide ample power to the peltier device, the motor, and the ultrasonic humidifier without any potential diode drops. Since there will be over 8A flowing through this circuit, it was more efficient to omit the control components. Also, since the power to those power devices did not need to be very clean, control components are unnecessary. The only attempt at cleaning the output voltage is the 10K microfarad capacitors at the output, which reduce the output voltage ripple (see Figure 6.4).

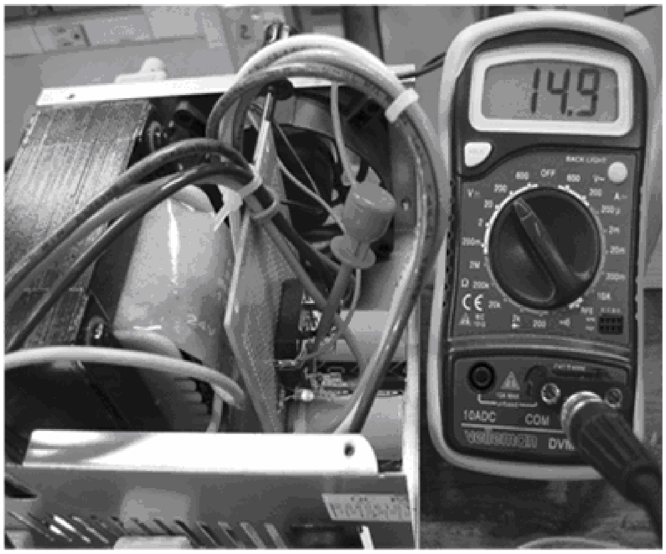



**Figure 6.4** The High-Current Power Supply is encased in a metal box with a fan. A multimeter reads the positive DC output of the supply.

## 6.3 Observations & Measurements

The D4XH11 transistors of the control supply indeed heats up significantly when the biodome is powered on, and heatsinks latched onto those transistors are indeed useful. The control power supply outputs a steady 15V with roughly 20mV of ripple without any load except the status LED's. With plenty of bypass capacitors on the control circuits of the biodome, the supply ripple voltage is reduced to negligible levels.

The high-current supply outputted roughly positive and negative 15V when the peltier is not being driven hard. When the peltier is turned on to heating, there is a 4V voltage ripple across the positive supply. When the peltier is turned on to cooling, there is a 4V voltage ripple across the negative supply. The transformer of the high-current supply is rated at 8A. Indeed, 8A seems to be the approximate current limit to the big power supply. When the ultrasonic humidifier is turned on, peltier heating is turned on, and motor is turned on, it becomes noticeable that each of the systems does not receive high voltage as it would receive without other loads. Nevertheless, the high-current power supply provided enough power for the biodome.

## 6.4 Error Analysis

A 30V transformer could have been used for the control supply. Since the transformer actually outputs a 36V signal and since that signal has been attenuated to 30V in the control supply, there is some power inefficiency and heat dissipation in the control supply. Also, the feedback resistor of the opamp in the control supply should have been connected directly to the output of the power supply. That way, the opamp reads and can regulate the true output voltage (instead of the output voltage after the voltage drop across the .5Ohm resistor).

# 7 Conclusion

After all four systems of the Analog Microcosm were integrated together and the biodome was assembled, all four systems functioned well enough to noticeably control the different environmental conditions of the biodome.

The temperature control system was able to drive the temperature to a range of over 30 degrees around room temperature. The peltier driver generated immense amounts of heat, and much heatsinking and fan-cooling was necessary to sustain the temperature control system's performance. The temperature control system drew the majority of the power from the high-current power supply and slightly affected the maximum performance of the other high-current components. With a bigger peltier, better heat dissipation, and a higher current supply, the temperature control system will be able to drive the temperature of the biodome to a much greater range.

The light control system successfully emulated the external light conditions from complete darkness to very bright sunlight. The infrared transmission system was able to reliably send data well over ten feet. The AC light dimmer's drawing power from the wall AC saved much power as well as transformer costs. With more powerful infrared signal emitters and receivers, the infrared transmission should reach even greater distances. Of course, radio frequency data transmission would allow the light control system to be able to function around many room obstacles and walls.

The humidity generation system successfully created cool mists of water above the column of water. With the humidity generator turned on for a couple of minutes, there was a noticeable change in the overall humidity level within the biodome. This change in humidity was displayed by the hygrometer system and its accuracy was confirmed with a commercial hygrometer. The humidity generator consumed quite a bit of power from the high-current supply and therefore conflicted with the temperature control system for power. If a higher supply voltage were used for the humidity generator, then the generated mist would be much greater in volume.

The gravity control system stably spun the centrifuge to the user's desired gravity. When objects were placed in the biodome platforms, the gravity control system smoothly accelerated them to over 40g's without any slip from the objects. Above 5g's, the platform with the objects seem completely horizontal to the Earth since the source of the generated gravity was the normal centripetal force. With more precisely machined mechanical components and a stronger motor, the gravity control system should be able to push the biodome environment to well over 100g's.

The actual biodome was miniaturized model of what could be a life-sustaining habitat. The biodome model was a 1000 cubic inch box with the control circuitry outside the actual box to conserve space. In the future, additional control systems such as audio, ozone, and wind could further enhance the biodome experience. We hope that someday a large-scale version of the biodome would be constructed such that it can be a practical research instrument for human habitat.

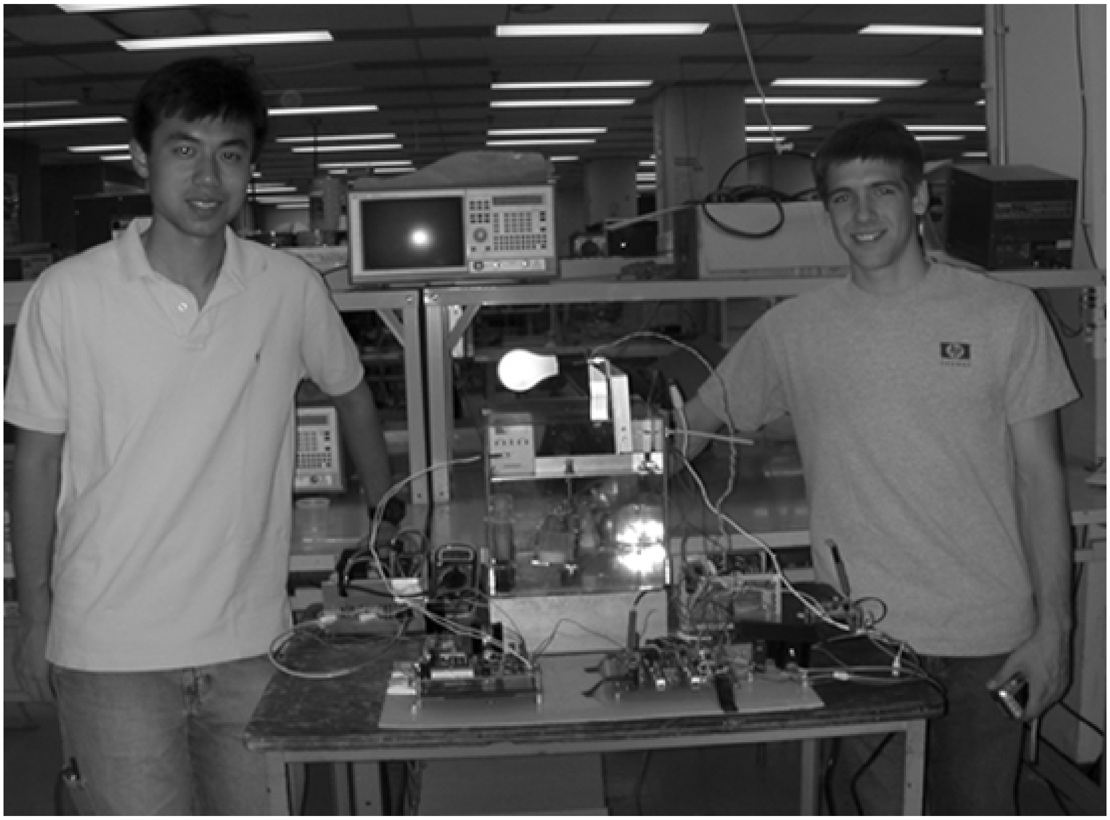
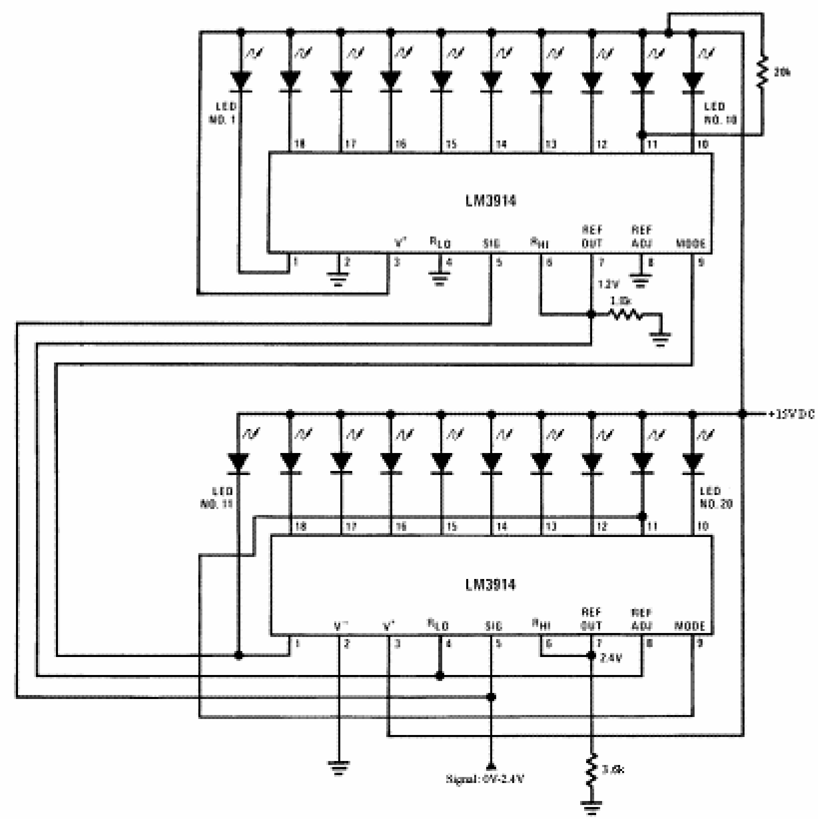


**Figure 7.1** The fully constructed and working Analog Microcosm.
On the left is Ji Zhang and on the right is Adam Kumpf.

# 8 Appendix

## Dual LM3914 LED Display Configuation

20 Segment LED Meter (Dot Mode)



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