Color Control Toaster

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Final Report for ECE 445, Senior Design, Spring 2017

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May 3rd, 2017

Project No. 51

Abstract

We designed, tested, and built a toaster to control toast color, decrease the likelihood of people eating unhealthy burned toast, and keep toast warm enough to butter for a longer period after it is finished. The toaster does this by ejecting toast once it turns a selected shade of brown and switching to a warming state to keep toast warm until it is retrieved.

Our toaster uses a color sensor to monitor the bread as it toasts, high power relays to interrupt toasting when the desired color is detected, and an SCR dimmer to create a warming state which does not affect the toast's color. A microcontroller monitors feedback from the color sensor and provides full closed loop control of the toasting and subsystems.

Contents

1. Introduction

It difficult enough to accurately set the timer of a toaster to achieve your desired toast color. When you try to toast frozen bread or different colored bread, this becomes nearly impossible. Also, if you forget to pick up your toast right when it pops up, you have to eat cold toast. We seek to improve control of toast color preferences, decrease the likelihood of people eating unhealthy burned toast, and keep toast warm enough to butter until retrieved, by creating a toaster that shuts off when the bread turns the correct shade of brown desired and switches to a warming state until the toast is removed.

Our project uses a color sensor to monitor the bread as it toasts, high power relays to stop toasting when the desired color is detected, and AC power electronics to keep the toast warm until retrieved without affecting the toast's color. A microcontroller monitors feedback from the color sensor and provides full closed loop control of the toaster's operation.

2 Design

2.1 Microcontroller

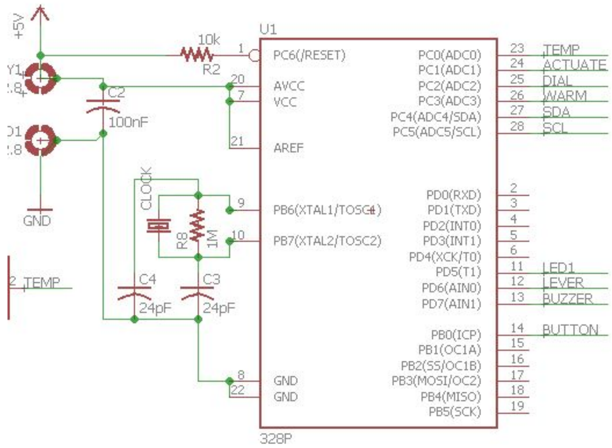

Figure 1. Microcontroller schematic

The ATmega328P receives data from the color sensor, the color dial, and the button and sends control signals to the relays, LED, and beeper. This block serves as the linker between all our inputs and outputs. It is powered and grounded with a capacitive filter, and driven by a clock and two 22pF ceramic capacitors. Appendix B outlines the software design of the finite state machine in detail.

2.2 Color Sensing

The RGB Color Sensor returns 16 bit red, green, and blue light values to the microcontroller through the SDA and SCL pins. Its physical placement also allows us to detect when bread is removed during the warming state. The color detection algorithm records initial color upon insertion, and monitors the change of these values as the sensor heats up to operating temperature. Once these values stabilize, the algorithm color spectrum from its as a percentage of its initial, stabilized value.

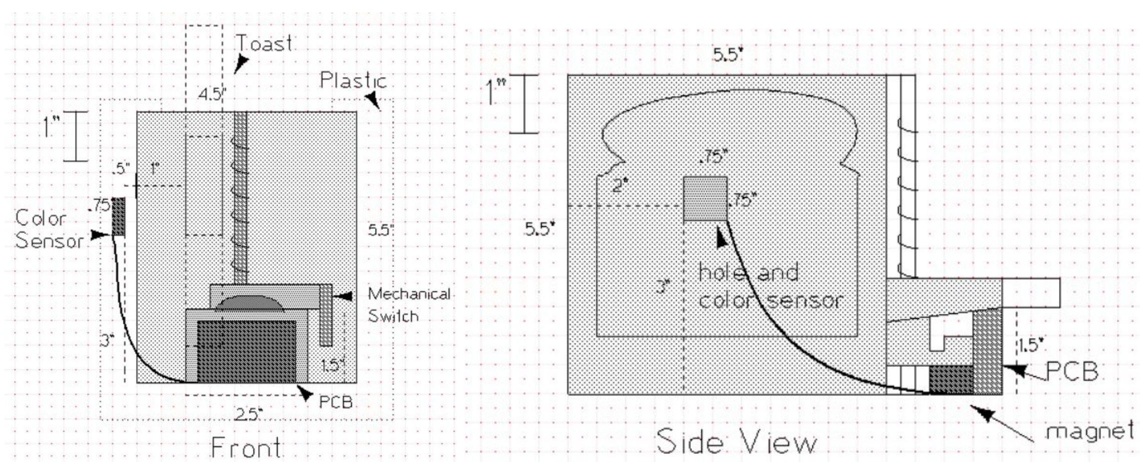

Figure 2. Physical design of color controlled toaster

Figure 2. shows the placement of the sensor for optimal sensing; far enough to stay cool (below 85 degrees celsius max) and close enough to detect the changing color of the toast.

A variable named color_sensed is compared to one called color_input. The first variable is equal to the sum of the green and the blue values measured at every moment divided by the maximum green + blue measured throughout the whole toasting process and multiplied by 100 to make it a percentage as shown in the following equation:

$$Color_{Sensed} = 100 * \frac{g+b}{\max{(g+b)}}$$

The variable color_input is a function of the potentiometer, the temperature and a correction multiplier that corrects the algorithm. This factor has to be used because, since we're using a proportional measurement, when we use light colored bread we measure a much bigger change in g+b than when we toast dark bread (i.e from raw to burned, white bread changes more it's color). The color_input variable is defined below, where all values used have been determined experimentally:

$$Color_{Input} = \left(97.7 + 2 * correction + \frac{Potentiom * (3.25 - correction * 3)}{1024}\right) * \sqrt{\frac{\sqrt{temp}}{\sqrt{710}}}$$

The correction factor has been defined experimentally. It needs to know how dark the bread introduced is. The way to do it for any lighting conditions is to compare the color measured without any bread inside, to the color measured with bread inside. The equation is defined and as follows:

$$Correction = 0.85 * \frac{0.85 * ((Color_{empty} - Color_{WithToast}) - 78)}{32}$$

78 is the difference in color brightness measured between having white bread and no toast inside the toaster. 38 is the difference in color brightness measured between whole bread and white bread. The equation above proved to be effective.

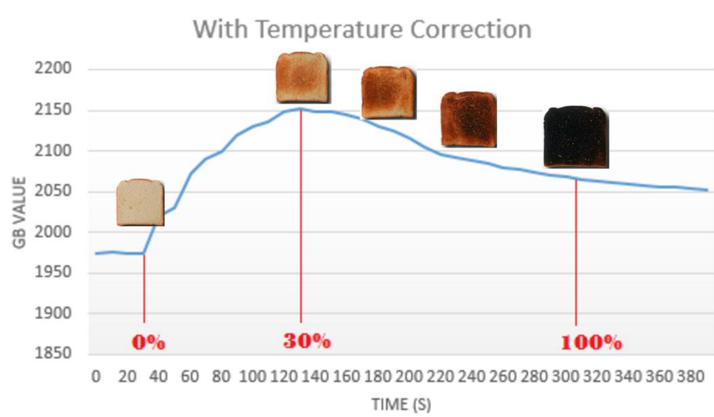

Figure 4. Temperature correction model

Figure 4 is showing the sum of the green and blue values over a toasting cycle experiment. The numbers in red show the “percent toasted” determined related to the dial input. Since we’re comparing the gb values to their maximum, we can only actuate using this algorithm if the dial is turned more than a 30%. That’s why if the dial is turned from a 0 to a 30% we use another algorithm to eject it that, depending on the potentiometer input and the temperature sensor reading, outputs a toasting time that will be set, as shown in the following equation and figure:

$$time_{in\ seconds} = PercentageOfPotentiometer * 4 * \frac{temp-210}{500}$$

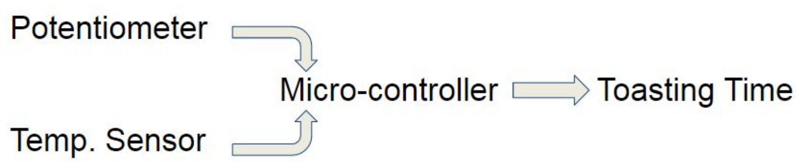

Figure 5. Toasting time output

2.3 Mechanical Switch

This device closes upon depression of the toaster lever and opens on ejection of the lever. It connects the anode of the heating elements to full power (120VAC) and connects the magnet driver to a 12V peak AC source.

2.4 Warming Circuit

2.4.1 Steffan-Boltzmann Equation

This circuit is parallel to the open mechanical switch, and provides the coils a reduced power during the warming state. We determined a temperature that would keep the toast warm enough to melt butter, but not continue to toast the bread, using the Stefan-Boltzmann equation. The total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature [1]. We measured the resistance of the nichrome heating elements of a toaster we intended to modify and found the resistance to be 18.5Ω at room temperature and 18.8Ω immediately after being disconnected at full power. We neglected this change in resistance due to temperature and calculated full toasting power at wall voltage using Ohm’s Law. $\frac{120^2}{18.5} = 778\ Watts$ We measured 310°F (427°K) to be the full power operating temperature of the heating elements, using an infrared thermometer. We know that the melting temperature of butter is 95°F (308°K). Substituting these values into the Stefan-Boltzmann equation above, we found the needed power to melt butter is 207W, which is 27% of full power.

$$\frac{P_1}{T_1^4} = \frac{P_2}{T_2^4}$$

$$\frac{778}{427^4} \times 308^4 = 207\ Watts$$

2.4.2 Power Electronics

Since we need to get this fraction from a 120 V_{rms} sinusoidal wave, we need to find the SCR rising edge trigger voltage that will put the area under the curve at 27% of the full root-mean-squared power. Since half the power is already blocked by the SCR, the problem is reduced to finding 54% of power on the positive voltage wave. The full positive area under the curve of a unit wave is 2.

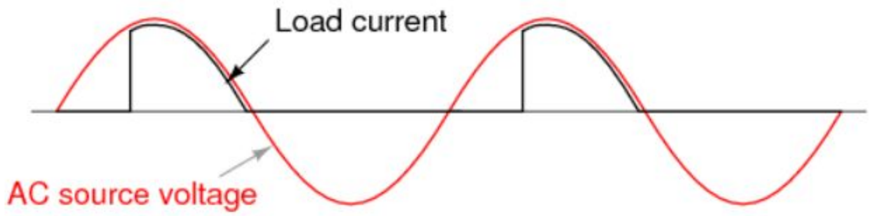

Figure 6. Example waveform of SCR rising edge triggering at x

$$\int_x^{\pi} sin(x) = .54 \times 2$$

$$-cos(\pi) + cos(x) = 1.08$$

$$x = cos^{-1}(.08) = 1.49\ radians$$

The voltage at this point on the rising edge and trigger voltage is $sin(1.49) \times 120\sqrt{2} = 169.16$ V. We can calculate the value of driver resistor R1 in Figure 6. using V_{on} = 1.7V and I_{on} = 8mA for our SCR [2].

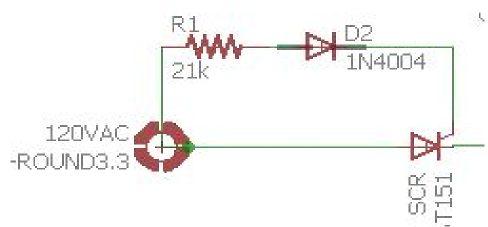

Figure 6. SCR circuit schematic

$$R = \frac{(V_{trigger} - V_{SCR_{ON}})}{I_{GT}} = \frac{(169.16V - 1.7V)}{8mA} = 20.9\ k\Omega$$

2.5 Magnet Driver/Lever Detector

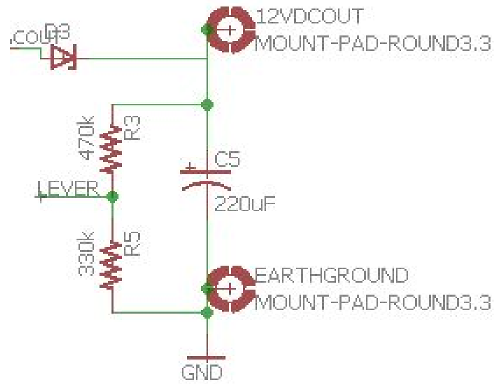

Figure 7. Lever detector schematic

The toaster's electromagnet, which is powered by the relay circuit, attracts a piece of metal on the handle when the lever is pressed, and holds it down against a stretched spring for as long as the toaster is in the pre-toasting or toasting state. Once power is cut, the toast is elevated by the spring to its initial insertion height. This device (simple half-wave rectifier) takes in 12 $V_{peak\ to\ peak} AC$ from a tap on the heating elements $\frac{1}{10\sqrt{2}}$ its full length from ground, and outputs 12VDC to drive the electromagnet that holds the lever down. It uses a diode and a capacitor in parallel as a half wave rectifier. To notify the microcontroller of the lever's status, a resistor divider with two large resistors regulates the magnet voltage from 12V to 5V. Logic high indicates that the lever is down, logic low indicates the lever is up. We needed to connect logic ground to earth ground for the signal to be compatible.

2.6 Relay Drivers

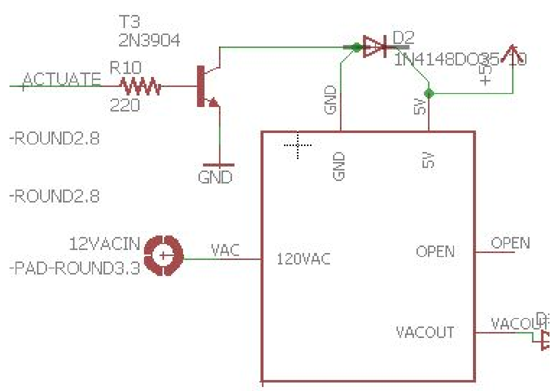

Figure 8. Relay driver schematic

To actuate a 120VAC warming state and 12V lever magnet using DC logic signals, we used npn amplifiers and JQX-15F/005 relays. The transistor amplifies the microcontroller's signal, which then powers a magnet that closes a mechanical switch inside the relay, which then supplies the main current. To induce the magnetic force to close the relay, we must send a current through the relay's coil (electromagnet). This magnetic force pulls a steel paddle and creates a connection with a copper paddle (like a switch). The logic diode here is required to give residual current in the coil a return path when it is interrupted during switching to off [3]. The relays galvanically isolate the microcontroller electronics and the user from wall-power. However, the microcontroller cannot supply enough current to hold the magnetic switch down on its own, and therefore requires an appropriately designed amplifier.

STEP 1: From Datasheet (JQX-15F)

$$Coil\ Magnetic\ Resistance = 27\ \Omega$$
$$Rated\ Voltage = 5V$$
$$Min\ Coil\ Voltage\ \ = 3.75V$$

STEP 2: Calculate Current: The relay's input current is the transistor's output collector current.

$$I = \frac{V}{R} = \frac{5V}{27\Omega} = 185\ mA$$

STEP 3: Calculating R10

The DC current gain β of our transistor is 75 at 10mA at 5V. We can find base current I_B by

$$I_B = \frac{I_C}{\beta} = \frac{185}{75} = 2.467mA$$

Using Ohm's law,

$$R_{10\ max} = \frac{V}{I_B}$$
$$R_{10\ max} = \frac{5V}{2.467mA} = 2026.75\ \Omega$$

Since we want out transistor to be in saturation and act as a switch, we chose a lower resistance of 220Ω based on experimental tests to eliminate audible switch bouncing, indicating a weak magnet.

2.7 User I/O circuits

We connected the following circuits to our microcontroller to help use and understand our toaster's operational states.

2.7.1 Push Button

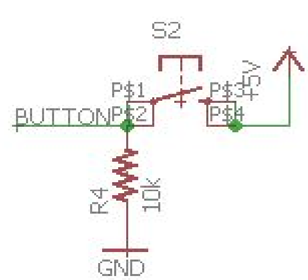

Figure 9. Sends a high signal to the microcontroller when pressed, used to return the toaster to the OFF state from any other state (Pre-Toast, Toast, Warming).

2.7.2 Dial

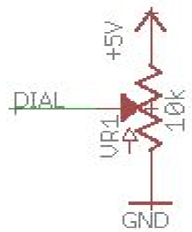

Figure 10. Sends an analog 5V-0V signal to the microcontroller mapping linearly to the 360° to 0° rotational position of a dial, which points to a graduated spectrum of experimentally found toast colors.

2.7.3 Status LED

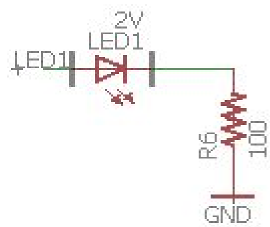

Figure 11. Driven directly by the microcontroller at 5V and 30 mA.

2.7.4 Beeper

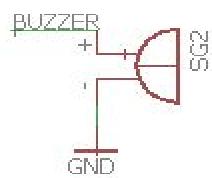

Figure 12. Driven by microcontroller to notify user to pick up toast during the warming state.

2.8 Power Adapter

We purchased a 120VAC to 5VDC wall-wart adapter rated for 1000 mA to help drive our relays at 185 mA each and microcontroller at 200mA independently of the heating elements and lever. It runs cool at 53% of rated capacity.

2.9 Temperature Sensor

This device measures the temperature of the color sensor and allows the microcontroller to calculate a thermal coefficient to integrate into its color readings. This is to help correct the inherent thermal effects on the sensor across operating environments and heat from repeat uses.

3. Design Verification

Our R & V requirements can be found on Appendix A. We managed to demonstrate a fully functional product at the time of our demo, satisfying all of the requirements. Our high level requirements were:

1) The toaster will toast bread to a specified shade.
2) The toaster will keep toast warm enough to melt butter for up to two minutes after toasting is completed, until toast is removed from the toaster.
3) The toaster will not power the heating elements when bread is removed from the toaster

When bread was inserted into the toaster and the lever was pressed, the toaster began toasting until the color sensed by the color sensor was equivalent to the color input on the dial. The warming mode also worked, keeping the toast hot for up to two minutes until picked up. Every time the toast was removed from the toaster, it shifted from the warming state to the off state. The warming mode didn't cause the bread to toast any more.

The most crucial parts for the correct functioning of our project was the finite state machine (Shown in Appendix B) controlled by the ATmega328 as well as the color sensing algorithm.

The state machine states were tracked with an LED (Figure 11.) that was on during the Off state, evenly blinking during Pre-toasting (same time on and off), unevenly blinking during Toasting state (less time on, more time off), and off during Warming state. It worked properly (See status LED and ATmega328 Requirements in Appendix A).

The color detection proved to work, thus fulfilling the requirements for the color sensor. We collected data by surveying people on different runs of the toaster (Figure 4.) , the color detection also proved to work during the demo.

The cancel button, lever detector, potentiometer, relay driver circuit and mechanical switch have proven to work. The verifications for them are trivial since without them working properly, the project would have failed.

The status LED and the sound beeper also proved to work. As we moved along the different states, they consistently showed their correspondent outputs.

4. Costs

4.1 Parts

PARTS					
Description	**Manufacturer**	**Part #**	**Qty.**	**Unit Cost**	**Total Cost**
ATmega328P-PU with Arduino Bootloader	Atmel	DEV-10524	1	$5.00	$5.00
Aluminum Capacitor	Panasonic Electronic Components	EEU-FC1E221	1	$0.42	$0.42
Diode Small Signal	Fairchild	1N4148	6	$0.15	$0.9
RGB Color Sensor	Texas Advanced Optoelectronic Solutions (TAOS)	TCS34725	1	$3.93	$3.93
Wall Adapter Power Supply	NLPOWER-CN	SFE5V2AD1	1	$12.94	$12.94
DC Electromagnetic Relay	Shaanxi Qunli Electric Co.	JQX-15F	2	$2.95	$5.90
2 Slice Toaster	Hamilton Beach	22005	1	$18.10	$18.10
Push Button	Omten Electronics	TSL12121/TSD1265	1	$0.53	$0.53
Temperature Sensor	Analog Devices Inc.	TMP36GT9Z-ND	1	$1.48	$1.48
Potentiometer	Panasonic	EVU-F2AF30B14	1	$1.02	$1.02
LED	China Young Sun LED Technology Co.	YSL-R531Y3D-D2	1	$0.35	$0.35
Piezo buzzer	TDK	ef532_ps	1	$0.72	$0.72
Resistor (1000 Ω)	Digi-Key Electronics	CF14JT1K00CT-ND	5	$0.10	$0.50
Resistor (1 MΩ)	Digi-Key Electronics	RNX1.00MHCT-ND	5	$0.10	$0.50
Resistor (21 kΩ)	Digi-Key Electronics	PPC21.0KZCT-ND	5	$0.29	$1.45
Capacitor (100 nF)	Addicore	117	1	$0.08	$0.08
Part Sub-Total					**$53.82**

Table 1. Parts & cost

4.2 Labor

Navigating through the Salary Averages page on the Illinois ECE webpage it can be seen that the average salary of an Electrical Engineer graduate is approximately $67,000/yr. [5]. Assuming a 52-week work period, each at the national average of 40 hours/week, the hourly pay rate can be calculated to be:

Hourly Rate = (Yearly Salary) / 52 weeks / 40 hours

Hourly Rate = $32.21

LABOR					
Service		**Hourly Rate**	**Hrs.**	**Total**
Electrical Engineer	Omar Ayala-Bernal	$32.00	225	$18,000.00
Electrical Engineer	Sean Cashin	$32.00	225	$18,000.00
Electrical Engineer	Ignacio Diez de Rivera	$32.00	225	$18,000.00
Labor Sub-Total				$54,000.00

Table 2. Labor & salary

4.3 Total Cost

Parts	$53.82
Labor	$54,000.00
GRAND TOTAL	**$54, 053.82**

Table 3. Total cost

5. Conclusions

5.1 Accomplishments

We are proud of what we accomplished in the 3 and a half months of this intensive course. Our team designed a PCB and implemented our very own toast-output algorithm that together made a color controlled toaster. During our demo, we were able to demonstrate our toaster toasting two types of bread for three incremental color shades: light brown, golden brown, and burnt toast. We were also able to show our device operating at reduced power during our warming stage.

5.2 Ethical considerations

As stated in the IEEE Code of Ethics, we have an obligation to our profession, "to accept responsibility in making decisions consistent with safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment" [7]. This directly applies to the design of our toaster, since it is imperative that we provide appropriate warning signs which let the user know that the surface is hot and to disallow the insertion of objects which could lead to a short-circuit and initiate a fire. Not only that, but equally important is "to be honest and realistic in stating claims or estimates based on available data" [7]. Since our software component will contain an algorithm which will monitor the change of color of a respective bread, whether wheat or rye, we should make it apparent that this is not like the standard toaster which uses time-based method, but has some signal processing aspect and a functional algorithm for handling varying scenarios/cases. Since the toaster is not a novel idea and we are redesigning its anterior designs we should, "improve [our] understanding of [the] technology; its appropriate application, and potential consequences" [7]. It was necessary to take apart a toaster and observe the basic functionality and design of old toasters, so that we could continue or improve its safety measures upon use. Due to this course's excellent structure we found it easy "to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others" [7].

5.3 Future work

Even though we are fairly satisfied with our results for the first prototype, some improvements could be made in the future. We could internally combine both plugs into one instead of simply plugging both into a power strip. Even better, we could eliminate the need for a 5VDC power supply by tapping the heating element at $\frac{5}{120\sqrt{2}}$ of its length from ground and run a half or full wave rectifier similar to the magnet driver circuit to provide unlimited power to all of our logic. We could add more color sensors to monitor multiple spots on the toast and average them, giving an overall more appropriate composite color. Mechanically, we could design a chassis that holds the whole thing together that is be more stable and visually appealing than duct tape.

References

[1] Stefan-Boltzmann Law, Available at *https://www.britannica.com/science/Stefan-Boltzmann-law*

[2] Thyristor Circuit, http://www.electronics-tutorials.ws/power/thyristor-circuit.html

[3] How to Build a Relay Driver Circuit http://www.learningaboutelectronics.com/Articles/Relay-driver-circuit.php

Appendix A Requirement and Verification Table

Table 4 System Requirements and Verifications

Submodule	Requirement	Verification	Verification status (Y or N)
Color Sensor	1. The colors of pieces cooked to the same detected level of brownness should also be indistinguishable to the human eye at least 90% of the time. 2. Survey of ten people results in at least 9 people agreeing that two toasts from two different trials of the same setting are the same color.	1. Survey of ten people results in at least 9 people agreeing that two toasts from two different trials of the same setting are the same color. 2. Survey of ten people results in at least 9 people agreeing that two toasts from two different trials of unequal settings (more than a 10% turn in the potentiometer from its dynamic range) are different colors.	Y
Push Button	1. Must trigger toast ejection when pressed, re-initializing toaster to the Off state.	1. Press button during a toasting cycle and verify that toast ejects and heating coils turn fully off.	Y
Lever Detector	1. Should detect whether the lever down or up within one second 99% of the time.	1. Monitor and time lever detector output for 100 up and downs.	Y
Dial/Potentiometer	1. When the dial is not changed, the variable sent to the microcontroller is stable +/- a 5/1024 V digital increment. 2. When the dial is turned at most 15°, the variable sent to the microcontroller increases at least two digital Increments.	1. Monitor variable from dial circuit on the microcontroller while holding it constant. 2. Monitor variable from dial circuit on the microcontroller while turning it 15°.	Y
ATmega328P	1. Shift between different states given particular inputs, without reaching a deadlock state 2. For each of the states the I/O pins should have the behavior defined in the state machine as shown in Figure 13, Table 5, and Table 6 of Appendix B.	(1 & 2). Use a status LED, with 4 different visualizations to determine which state the state machine is on and while in a state use a multimeter to ensure that the voltage reading on the output pins are HIGH, as expected from Table 3.	Y
Status LED	1. Must turn on observably from 3 meters away with normal overhead household lighting conditions when toaster reaches warming state.	1. Visually determine if LED is on or off from 3 meters away and verify toaster's state.	Y

Sound Beeper	1. Must be clearly audible from 6 meters away above household background noise (65dB) when toaster reaches warming state.	1. Stand 10 meters away and determine the beeper is on or off state correctly at least 9 out of 10 times over at least 2 background conversations.	Y
Power Adapter	1. Needs to hold voltage between 1.8 and 5.5V (as found on the ATmega328P datasheet for a 16Mhz clock) over output current range 0- 450mA to power our electronics. (Relay + Relay + Microcontroller = 185 + 185 + 80 = 450mA max).	1. Measure open circuit voltage and then attach a 10Ω load to the power supply. Use an ammeter to verify the load current is at least 450mA. Use a multimeter to measure the voltage across the GND and VCC terminal of the power adapter and verify it is within the required range at both bounds.	Y
Relay Driver Circuit	1. Must be able to open and close a relay based on the logic input signals (here defined) from the state machine. The relay turns on during a logic high at a current of strictly less than 40mA. The relay turns off when signal falls below 1.8V. The power required for the relay and driver itself itself need not come from the signal and therefore has no necessary consumption limitation. 2. Relay output must be capable of conducting and interrupting 6.8A +/- 10% at 120VAC +/-5%.	(1 and 2). Both input and output requirements are verified if Relay 1 closes when toaster switches to Warming state and opens when toaster switches back to Off state Also, Relay 2 opens to eject toast when toaster switches from Toasting to Warming and recloses within 1 second.	Y
Magnet Driver	1. Should hold magnet down during Toasting state and engages within one second of the lever being depressed.	1. Hold down lever when toaster is in Off state for 1 second and verify that the magnet engages and continues to hold the lever down for the duration of the Pre-Toasting and Toasting states for 9 out of 10 tests.	Y
Mechanical Switch	1. Turns on and off heating elements when opened and closed.	1. Test that heating elements turn when toaster switches from Off to Pre-Toasting state and reduce power when switch opens and toaster switches to Warming state 9 out of 10 times.	Y
SCR Circuit	1. Can supply 25% +/- 5% of 76 6W at 120 V AC to heating elements for up to 3 minutes. 2. Tunable to modulate the power between 25-50% with a resolution of 7.66W of power.	(1 & 2). Supply 120VAC to the SCR circuit with an 18.8 Ohm load for 3 minutes and monitor SCR.	Y
Temperature Sensor	1. Gives accurate readings as expected from 0 to 70°C, which is the upper rated operating temperature for the color sensor.	1. Compare temperature readings from sensor to those of thermometer at 0°C and 70°F.	Y

Appendix B Finite State Machine

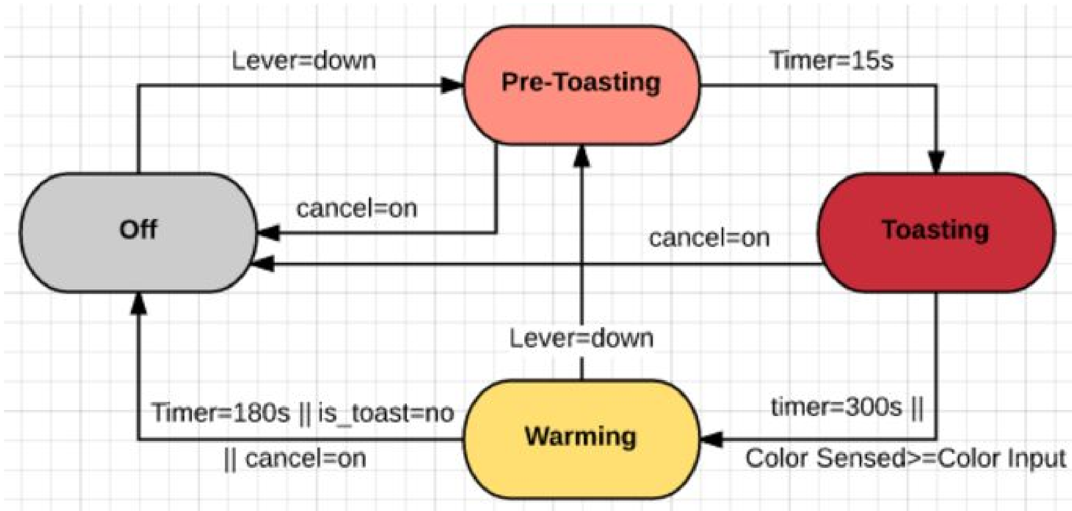

Figure 10. State Machine for Color Control Toaster

Input Variable Name	Values	Obtained from
Lever	Up/Down	Crash sensor
cancel	On/Off	Cancel button
Timer	Int measuring seconds.	Clock and microcontroller (reset every state change)
is_toast	Yes/No	Color sensor
Color Input	Int measuring color desired	Potentiometer and microcontroller
Color Sensed	Int measuring color detected	Color sensor and microcontroller

Table 5. State machine input variables

Output Variable Name	SCR Relay	Mech Switch	Magnet Driver Relay	Beeper	Led
Off	Off	Off	Off	Off	On
Pre-toasting	Off	On	On	Off	Even blink
Toasting	Off	On	On	Off	Uneven blink
Warming	On	Off	Don't Care	On	Off

Table 6. Descriptions of states for finite state machine