Remotely Connected Electric Field Generator for Particle Separation in a Fluid

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April 24, 2016

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Abstract

This document details the design and implementation of a remotely controlled electric field generator. The goal of this design is to provide an easy interface for manipulating the output voltage and frequency of a circuit utilizing network communications in order to generate an electric field. This electric field, when applied to a fluid over a long period of time will cause particles in the fluid to separate. The hardware and software components used to accomplish the aforementioned goal are described in detail as well as the interconnections between these components. A guide describing the procedure by which a person may set up and use this implementation is provided.

1 Introduction

New research has shown that certain particles may be separated from fluids through dielectrophoresis. This process involves applying an electric field to a fluid. The field may be manipulated in order to attract or repel certain particles. The particles the electric field will attract or repel depends on characteristics of the electric filed which may be controlled by varying the voltage and frequency of the electronics driving the field.

This technology has many useful applications in health care. The proposed end use of this equipment is for separating particles contained in bodily fluids, such as spinal fluid. Such medial applications could be useful in filtering these fluids for testing purposes.

Being capable of separating though the application of an electric field would represent an advancement over existing solutions. Separation in this way introduces a new method of testing which could be more precise when compared to existing technologies.

Imagine if a centrifuge, an expensive piece of medical testing equipment which separates particles in bodily fluids, could be replaced by a much cheaper device. This cheaper device could even have the potential for more well-defined separation among particles. Such a device, if it could be made to exist, would have large, positive, economic consequences for creator. This project could construct the foundation for such a device.

This project is part of a larger initiative to build a device which is capable of separating particles in fluids utilizing the dielectrophoresis phenomenon. This phenomenon works though the application of a quickly changing electric field. The change in the electric field affects different types of particles differently leading to a separation among types of particles. This process must continue for a long period of time in order for a great degree of separation to occur. Often times this process can take hours.

2 Project Definition

In this implementation, an electric field is applied to two metal plates. Through varying the voltage and frequency applied to these plates, the properties of the electric field may be changed. Modifying the properties of the electric field will affect separation of fluids and is therefore desirable.

Our job is to construct a system containing an electronic circuit capable of providing the voltages and frequencies required to drive a pair of metal plates. This system must enable the circuit to be controllable through the use of a web interface. In addition, a small form factor must be maintained.

The system must be able to generate up to a 60 V peak-peak sine wave with user-controlled variable frequency from 10 kHz to 1 MHz. Due to the time requirements of dielectrophoresis, this output must also be capable of being maintained for long periods of time. In addition, the user of this system should be capable of controlling it remotely. The implications of this on the implementation are that there must be some way of communicating with the device through a network.

2.1 Deliverables

There are three items which must be constructed for this project: frequency control circuit, voltage control circuit, and software components.

For the analog circuit components, functionality of the circuit will be tested using an oscilloscope to verify the requirements have been satisfied. This method can also be used to ensure the output signal contains minimal amounts of noise and distortion.

The construction of this device is the first phase of the project. After the completion of this component, the device will be used to experiment with particle separation in various fluid types. These experiments constitute the remainder of the project. For these experiments our advisor at Minetronix, John Pritchard, will be the main source of guidance and testable material.

2.2 Constraints

Constraints on this project fall within the size, voltage, and portability domains.

The size requirements of this project are directly related to the portability of the final design. The design requirements specify this system must be easily and quickly moved around from one workstation to another. The maximal allowed size is approximately the size of a backpack with smaller sizes being more desirable but not explicitly required. With the electronics currently being used, these requirements will easily be met.

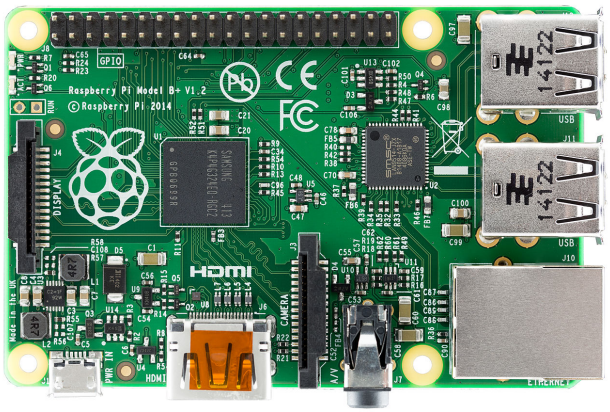
Another constraint arises from the power supply requirements. The power supply must deliver at least 60V DC in order to feed the amplifier circuit. Due to this, the final design requires a power brick similar to one which would be used to charge a laptop. Importantly, this would require the device to be plugged into a wall outlet. This is not seen as an issue. Every location this device will operate will most likely have other equipment with similar power requirements.

In order to use this system, there are other items which are required apart from the device itself. The first requirement is a network connection between the device and a computer. This connection is necessary to be able to interact with the web server hosted on the Raspberry Pi. Without a computer to interact with this system there is no practical means of utilizing the device's functionality. The next requirement, as mentioned above, is a network connection to the Raspberry Pi. The third system re-

quirement is a standard wall outlet to accommodate the power needs of the system.

2.3 System Analysis

A user will interface with this system though the web interface. This web interface may be accessed by typing the IP address of the device into a standard web browser. The interface will allow the user to choose the values for Voltage and Frequency. Once these values have been entered, update scripts on the Raspberry Pi will set the voltage and frequency output of the circuit according to the values entered.



3 Functional Decomposition

This system has four fundamental functional blocks. These include the Web Interface, Raspberry Pi, Minigen Signal Generator, and Amplifier Circuit. The project will be described in terms of these components and their interactions.

3.1 Raspberry Pi

The Raspberry Pi will act as the bridge between the user and the circuit. The Raspberry Pi will host a web server allowing the user to interact with the system. Based on the results of this user interaction, the Raspberry Pi will update the state of the GPIO pins. The GPIO pins connect to a circuit causing the output to change based on their state.

In addition to hosting the web server the Raspberry pi is used to communicate with the Minigen Signal Generator and amplifier circuit. This communication is accomplished via the Raspberry Pi's SPI interface and GPIO pins respectively.

There are many potential solutions other than the Raspberry Pi. So what motivated the choice of the Raspberry Pi? The answer is as would expected, the Raspberry Pi has capabilities which allow it to act as a communicator between the user and the circuit. While other devices have similar capabilities, such as an Arduino, the requirement of having a web interface is a lot easier to implement on the pi compared to most Arduinos.

Another factor consistent with the goals of the project is the small form factor of the Raspberry pi. While there was no exact specification, it was made clear that smaller implementations are preferred. On top of the above mentioned factors the Raspberry Pi is also inexpensive. Given all of these factors, the Raspberry Pi seems like an ideal fit for this project.

3.2 Minigen

The Minigen Function Generator device controls the frequency output by the circuit. Varying the frequency is accomplished by writing to registers present on the Minigen. This communication is completed over SPI between the Raspberry Pi and the Minigen. The frequency produced is a function of the values contained in the Minigen's frequency registers.

The Minigen outputs a waveform from -0.5V to 0.5V. This waveform may be a triangle, square, or sine wave. The voltage output by the Minigen is not variable. Given that the design specification requires a variable voltage, the voltage needs to be adjusted separately. Accordingly, the output of the Minigen is supplied to the input of the amplifier circuit.

The Minigen is controlled by setting five registers, two registers for frequency, two for phase shift and one as a control. There exists no need for phase shifting to meet the design requirements, however the frequency and control registers are needed. By having two frequency registers, data can be sent to one register while it is not in use, followed by a write to the control register to use this register. This allows for a nicer gradient, because the frequency will not change until the entire frequency register is written. The control register also allows for changing between sine, square and triangle waveforms. In the event that the frequency needs to be finely adjusted, this system utilizes the functionality of the control register to modify the way in which writes to the frequency registers are received. The way writes are received by the frequency registers can be varied between two modes. In one mode, two consecutive 14-bit writes to a frequency register are used. In the other mode, one write to the lower 14-bits of the 28-bit frequency register is used. This functionality affords the ability to accurately dial in small changes to the register values quickly.

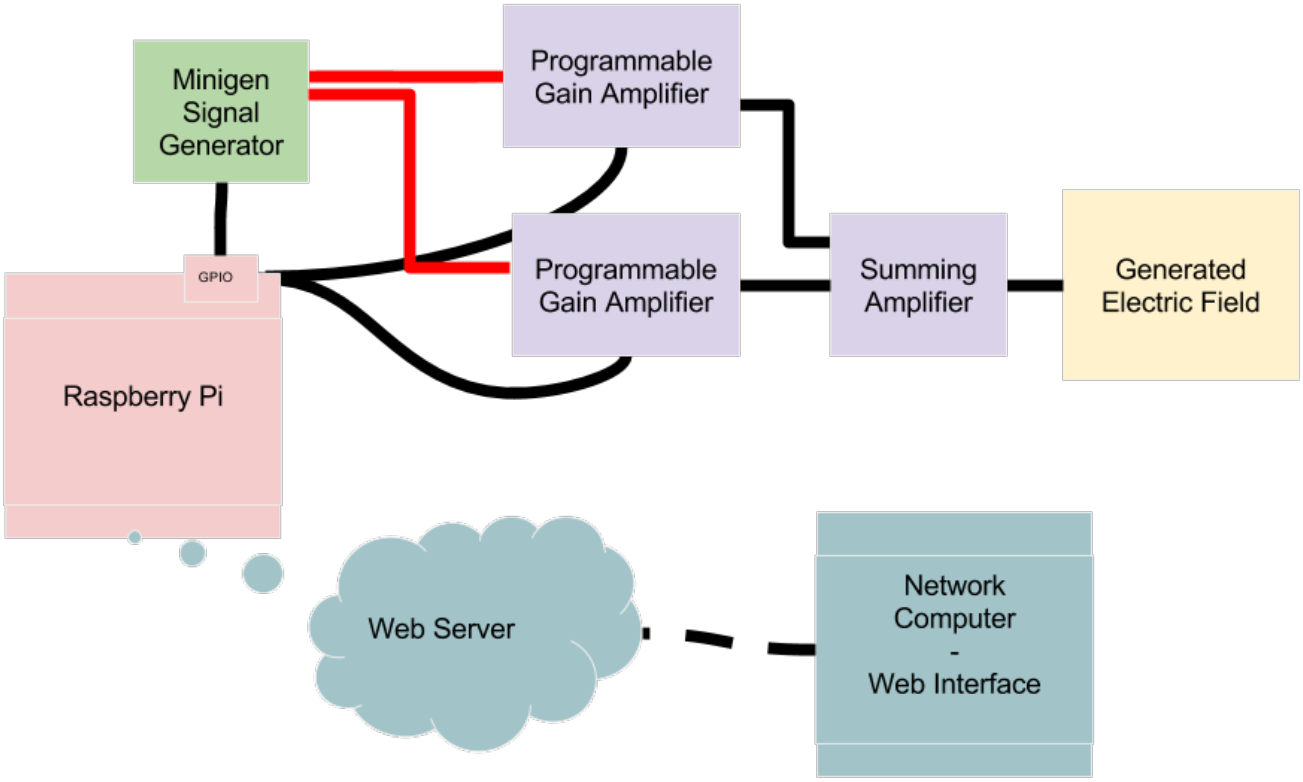
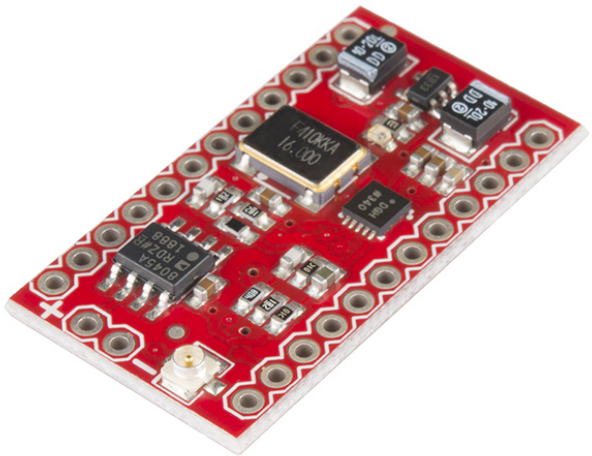


Figure 1: Block Diagram provides an overview of the system components.



Until this point, several functional benefits of the Minigen Signal Generator have been discussed. An additional benefit which increases the practicality of this solution is the Minigen's small form factor. The small chip size allows the Minigen to fit easily into a small case with the Raspberry Pi. This is consistent with the system's requisite small footprint.

3.3 Amplifier Circuit

As mentioned in the previous section, the output of the Minigen Function Generator is applied to the amplifier circuit as input. The amplifier also receives input from the GPIO pins of the Raspberry Pi. These GPIO pins act as switches which help to control the output voltage. Based on these inputs the amplifier circuit manages the overall voltage and frequency output.

The project requirements state that the system must generate signals which range from $1V_{pp}$ to $60V_{pp}$. To accomplish this, various circuit components were used to accomplish the amplification. The overall scheme is to split the output voltages into three different ranges. One component is used to adjust the voltage within each of the ranges while other comp are used to change the range the voltage adjuster is acting within.

A schematic illustrating the amplifier circuit as a whole is depicted in Figure 2. This diagram follows the signal from the

output of the Minigen Function Generator to the overall output of the circuit after the summing amplifier. The Minigen output feeds directly into two stages of amplification. Each stage containing a PGA and an amplifier. The upper stage in the diagram contains a gain of 7.5 while the lower stage contains a gain of 1.

The lower stage has many more components than the top stage. The reason for this is the OPA552 operational amplifier which is being used to preform the amplification, is optimized for a gain of five or more. For gains lower than five, there must be additional components added. The effect of not adding these components is a dramatic increase in the frequency of the output.

3.3.1 Programmable Gain Amplifier(PGA)

The programmable gain amplifier or PGA is core mechanism by which voltage is modified in the circuit. As can be seen in the circuit diagram 2, There are two PGA's utilized in the circuit. Each PGA controls one stage of amplification. The PGA has 8 possible output gains, 0-7. These gains are set though the use of three GPIO pins. Each GPIO pin is connected to one input pin on the PGA. The gain of the pga is selected by the binary number encoded by these bits.

3.3.2 Amplification Stages

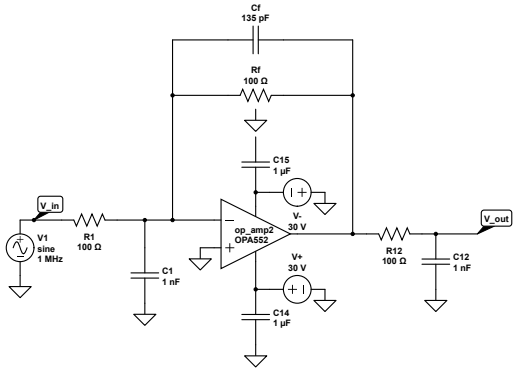
There are two amplification stages pictured in Figure 2. Each of these stages takes input from the Minigen. The first component in each stage, the PGA, takes this input, applies a gain K in range $0to7$, then inputs this signal to an OPA552 operational amplifier. These amplifiers output to the input of the summing amplifier.

The gain, A, of these amplifiers after the PGA's are chosen to maximize the voltage resolution. The overall voltage requirement is the circuit must output $1to60V_{pp}$. In order for the output of the summing amplifier, which follows the amplification stages, to be capable of outputting $60V_{pp}$ the output of all voltage stages must sum to this value.

$$A_1 = gainofstage1amp$$
$$A_2 = gainofstage2amp$$
$$V_{m1} = maxvoltageofstage1$$
$$V_{m2} = maxvoltageofstage2$$
$$V_{m1} + V_{m2} = 30V$$
$$V_{m1} = \frac{V_{m2}}{7}$$
$$V_{m1} + 7V_{m1} = 30V$$
$$8V_{m1} = 30V$$
$$V_{m1} = \frac{30V}{8}$$
$$V_{m1} = 7.25V$$
$$V_{m2} = 22.75V$$
$$A_1 = \frac{V_{m1}}{7}$$
$$A_2 = \frac{V_{m2}}{7}$$
$$A_1 = 1.0357\frac{V}{V}$$
$$A_2 = 3.25\frac{V}{V}$$

The above equation derives the appropriate gain for the amplifier in both stages of the circuit. These Gains A_1 and A_2 represent these gains. Notice that one of the gains is greater than 5 while the other has a gain close to unity. This is an issue for us because the op-amp, OPA552, which we are using in our circuit is optimized for a gain of 5 or greater.

If the gain is under 5 additional components are necessary to make the op-amp stable. Unfortunately these components have two negate affects. First, these components act as a filter. Second, there components apply a phase shift to the output. This increases the complexity of the circuit. There must be some additional components added to ensure the phase shift of both amplification stages are the same.



gain of 1 op-amp with

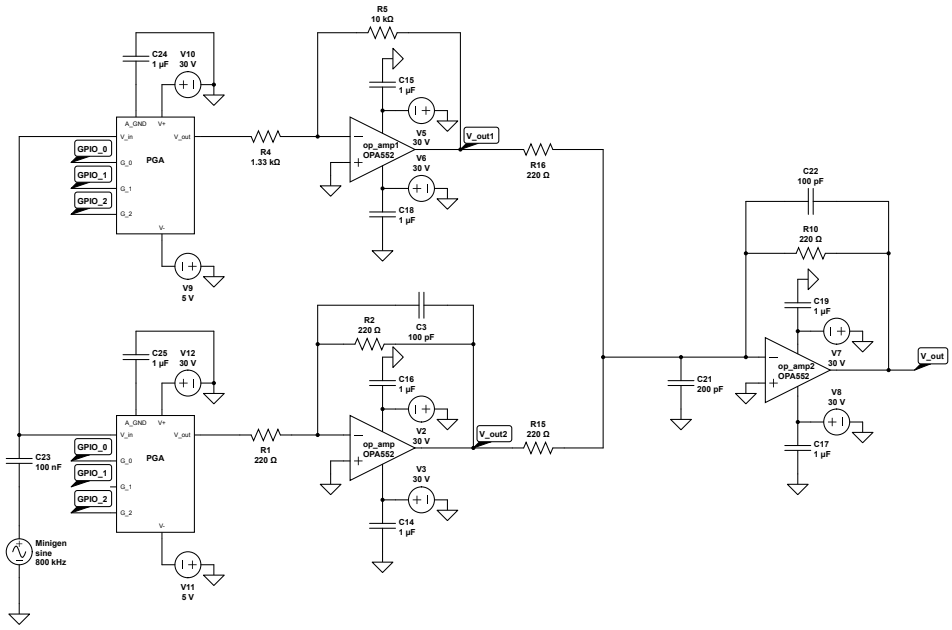


Figure 2: Amplifier circuit design to vary voltage within range $1V_{pp}$ to $60V_{pp}$.

frequency compensation and phase shift correction.

There are two amplification stages. Due to the frequency compensation necessary one one stage, the phase shifts of these stages were initially different. In order to make the phase shits the same, a resistor in series with a capacitor to ground were applied to both the input and output of the frequency compensation amplifier. The end result is that we are able to modify the phase shift according to this transfer function:

$$\frac{V_{out}}{V_{in}} = \frac{-R_f}{(-j * \omega * C_{12} * R_{12} + 1) * (j * \omega * C_f * R_f + 1) * R_1}$$

This function allowed us to predict the phase shift amount for a given frequency. This knowledge allowed the modification of the values to reproduce the phase shift present in the other stage.

3.3.3 Summing Amplifier

The summing amplifier is the last component in the amplifier circuit. The overall voltage range which needs to be produced is divided into two segments. Each of these segments have their output connected as input to the summing amplifier. The advantage of this design is that it allows for an increased number of voltage steps compared to what is allowed for by a single PGA.

The output of the summing amplifier conforms to the above equation. As can be seen in this listing, the amplifier will take take the input signals and sum them. If, for example, the input voltages are $3V$ and $10V$, the output will be $13V$.

The negative effects of choosing to implement the summing in this way is that large constraints are placed on the amplifier. The summing amplifier will need to be capable of producing a sine wave at $60V_{pp}$ and $1M_{hz}$. This means the slew rate of this op-amp will need to be $120\frac{V}{\mu s}$. These constraints are fairly limiting and require an expensive op-amp to meet.

4 Software Components

The web interface displayed by the web server hosted on the Raspberry Pi is the user's window into the system. Through this interface, the user can seamlessly control various components of the system cause the desired voltage and frequency to be produced. Previously covered are the hardware components used to accomplish this. This section describes the software counterparts used to control the hardware.

4.1 Technology Choices

There are many tools to accomplish any job. In the software domain there are many utilities and programming languages which could have been used to accomplish the goals set forth in this project description. Why then did were apache 2 and python chosen? What could be the advantage of using these software tools over others? This section seeks to answer the aforementioned questions.

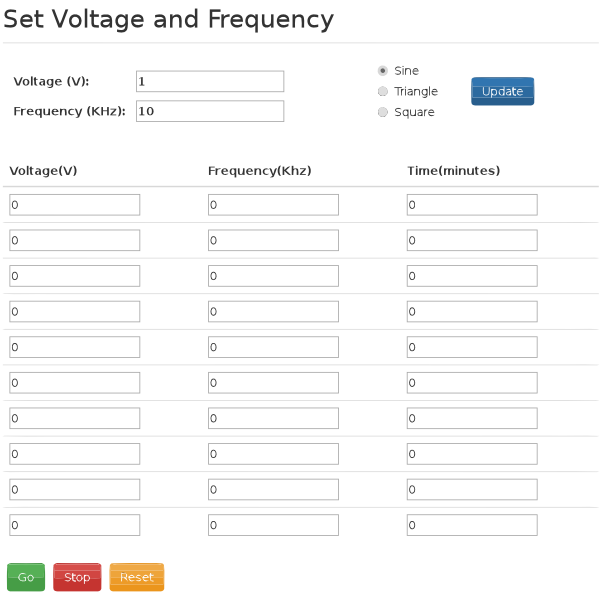
Apache 2 was chosen as our web server due to it's ease of installation and use, good documentation, and large user base. In some respects, Apache 2 is often the default choice for web server applications. Only if there are special or advanced features necessary, which are not available by utilizing Apache 2 would there been consideration for other applications. Apache 2 is a very well known web server implementation with a lot of users. Any foreseeable problem for this project will likely have information available from other people having faced the same or similar problem.

Python is a powerful scripting language which is designed around the ideals of quick and pretty code. That is, the goal of Python's creators was to write a language which would be easily readable, quick to write, and have a lot of functionality. For this project, time is of the essence. Any intelligent choice of tool which will help to speed the process of completing one aspect of the project will allow more time to be spent on another. Python also has many useful libraries such as spidev and RPi.GPIO which were used in this project. The relative ease of programming in combination with the useful and relevant libraries made Python the clear choice for this project.

4.2 Web Interface

The web interface is hosted on the Raspberry Pi using an Apache web server. This web server displays an interface which allows the user to set a voltage and frequency output by the system. The interface is simple and interactive, implemented using cgi-scripts on the Apache web server.

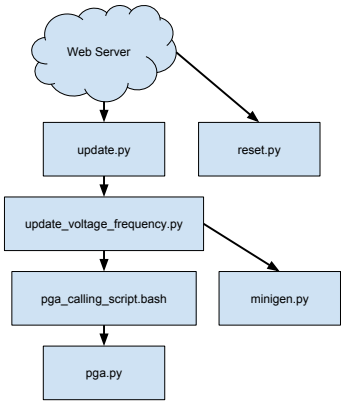
Our implementation provides several functionalities. Among these are the ability to set: voltage and frequency, sine or triangle or square waveforms, and the ability to set a voltage and frequency for an amount of time. The table displayed in the figure below provides the ability to set voltage and frequency for the number of minutes specified. The "Go" button will cause the first voltage and frequency to be set for the corresponding amount of time. After the time has expired, the next voltage and frequency will be set for the corresponding amount of time. This process continues until the table entries are completed or the user presses the "Stop" button.



4.3 Web Server

The primary function of the web server is to communicate with the Raspberry Pi. This is the primary method of control afforded to the user by the system. The web pages displayed by the server have the ability to control the voltage and frequency output by the circuit.

Displaying this interface is accomplished by running an Apache web server on the Raspberry Pi. When the user clicks update, the server could executes a cgi-script performing the update functionality.



4.4 Modifying Frequency

The frequency output by the circuit is controlled by the Minigen Function Generator. Thus the software components used to modify the output frequency are in essence a method of communication with the Minigen device.

The process begins when the user enters a new frequency value into the web interface and clicks the "update" button. The *update.py* script parses the parameters contained in the URL resulting from the user's update request. These parameters are than passed on to *update_voltage_frequency.py* which determines the appropriate update procedure with which to call *minigen.py*.

minigen.py is a script, written in python and uses the spidev library to communicate with the Minigen. This communication is tricky due to the layout of the registers on the Minigen. There are five registers: two frequency registers, two phase registers, and one control register. A combination of these registers need to be written to cause the Minigen to produce the correct output.

Take the typical use case for this project of modifying the frequency. There are two frequency registers. Only one of these are active at a time; active defined as the output of the Minigen being derived from that register. The control register must be written in order to change the active register. Further complicating this process is that the frequency registers are 28 bits wide, but the Minigen only accepts 16 bit writes at a time over SPI. In addition, there are two modes in which frequency can be written depending on the settings of the control register.

Sorting though this madness, eventually it was found the process for writing the frequency register is as follows. First, modify the control register to a known value so that the inactive register may be written and the method of writing the frequency register is set to fine. Fine frequency modification means both MSB and LSB of the frequency register can be modified. Second, Preform two consecutive 16 bit writes to the Minigen with the first bits addressing the frequency register, and the remaining 14 bits containing either the LSB or MSB of the requested frequency. Third, Preform a final write to the control register to make the frequency register which has just been written the active register.

The other problem which needs to be solved is, of course, what values need to be written to the frequency register. That is we need to convert the decimal value given to a binary string to be written. This is accomplished by first dividing by the minimum step size of the Minigen. The resulting value gives the number of steps necessary to achieve the value wanted. The number which is written the frequency register is the number of steps. Finally, this step value is converted and sent in the order, MSB than LSB.

4.5 Controlling Voltage

4.5.1 Programmable Gain Amplifier(PGA)

The method of interaction with the PGA is though three GPIO pins which encode a binary number indicating the desired gain. The software written for the PGA than has two objectives. First, the gain of each stage must be computed. Second, the gain of the PGA needs to be modified.

In order to compute the gain of each amplifier, two pieces of information are needed. What is the gain of the amplifier in this stage and what is the requested voltage. The gain of the amplifier is know at design time and the requested voltage is gained through user interactions with the web interface. Once these this information is known, the problem reduces to one similar to counting change.

In the counting change problem, a person is trying to create a monetary value with the fewest number of coins possible. This problem is solved by using as many of the biggest value coin as possible without going over, then using as many of the second biggest value coin as possible without going over, ect. In this example, the coins are analogous to the gains of the amplifiers in each stage of the circuit while the monetary is analogous to the requested voltage.

The approach used in our implementation is similar to that of the counting change problem. In order to find the again of a PGA in a given stage, we compute how many of that stage's amplifier gain could fit in the overall requested voltage. All stages conform to the following equation:

$$A_{PGA} = floor(\frac{RV}{G_{AMP}})$$

where A_{PGA} = gain of pga,
RV = requested voltage remaining after voltage allocated to previous stages has been removed,
and G_{AMP} is gain of amplifier in series with the PGA.

Modification of PGA gain requires the toggling of GPIO pins on the Raspberry Pi. The pins should be set to a binary value equal to the requested gain. A Python object utilizing RPi.GPIO was created. This script preforms the necessary mapping of gain value to GPIO pins and modifies the value of GPIO pins accordingly, but there is a problem.

Root access is required to modify the values of the GPIO pins, and the Apache 2 web server protects against cgi-bin scripts executing commands as root. Our solution is to call a bash script with the arguments necessary for the Python object to set GPIO pins to a specified gain. The intermediary bash script works by *echo*ing a short python program and piping the output of this *echo* command to the input of *sudo python* This circumvents apache's protection while still allowing the use of Python.

5 Cost Considerations

The monetary cost of this project is fairly low. The precise costs of components in the future are unknown, but a table of current prices has been provided along with the necessary quantity of each component. The projected cost of op-amps and other electronic components is minimal. The largest expenditure of the project is the purchase of the Raspberry Pi 2 and Minigen Function Generator. Other necessary components are a micro SD card, resistors, capacitors, and op amps.

In the following table, costs for capacitors and resistors are computed at .1 dollars each.

Item	Part Number	Quantity	Price($)
Raspberry Pi 3 Kit	**-**	**1**	**49.99**
Micro SD card	**-**	**1**	**9.99**
Minigen Function Generator	**AD9837**	**1**	**29.95**
Resistor	**10K Ohm**	**1**	**0.10**
Resistor	**1K Ohm**	**1**	**0.10**
Resistor	**330 Ohm**	**1**	**0.10**
Resistor	**220 Ohm**	**3**	**0.30**
Capacitor	**1uF**	**2**	**0.20**
Capacitor	**.1uF**	**11**	**1.10**
Capacitor	**.1nF**	**6**	**0.60**
Op Amps	**OPA552**	**3**	**4.41**
PGA	**pga 6910-3**	**2**	**8.00**
Total	**-**	**-**	**104.84**

6 Testing

In order to discuss testing in a more clear way it is useful to define a number of steps in the testing process. Each of these steps can than be developed for each of the various components to the project. The flow of the testing process involved an iterative process of:

1. Theorize a design
2. Acquire necessary components
   - knowledge
   - hardware components
3. Implement design
4. Understand problems
5. Return to step 1

It is important to recognize that many of these steps may be different for different components. A program written to be run by the web server will inevitably have different testing requirements from a new integrated circuit component.

6.1 Testing Process

Each phase of the testing process poses unique challenges. Here are presented some of those challenges and how each phase related to specific aspects of this project. Importantly, the time it takes to complete a testing cycle varies drastically. Hardware components, for instance, take far longer to test as they must be constructed on a breadboard in order that measurements may be taken with lab equipment. The length of the testing cycle is directly proportional to the extent to which a component may be tested. For objects with long testing cycles, much more time is spent in the theorizing a design phase compared to objects with shorter testing cycles.

6.1.1 Theorize a design

In this phase of development, the goal is to determine:

- A design which *should* work
- What knowledge is needed to complete an implementation
- What physical components will be necessary

Often times it is wise to determine the above for multiple potential solutions. The time necessary to implement each solution can then be estimated and weighed against the potential for success with such a design.

Which design is chosen for implementation is some combination of the estimated time and potential for success. The decision to abandon a design is often due to a change in one of these factors. This change can occur either in the current design or in one of the alternative designs. An example which might motivate abandonment of a particular solution might be the finding that a certain hardware component contained in the current design is incapable of working at a high enough frequency to produce the overall output.

While the theory of testing hardware and software is similar, in practice these activities can be very different. In this project, however, they became somewhat similar due to the fact that program code is written in order to interact with hardware components. In both cases, the physical output of either GPIO pins on the Raspberry Pi or output of a circuit component must be view on an oscilloscope.

6.1.2 Acquire necessary components

The goal of this phase is self-explanatory. The necessary components must be acquired. While the goal may be clear and simple; it may not be easy. The term acquisition may refer to physical hardware, but it also refers to the knowledge necessary to implement a given system. Every potential implementation has a knowledge component. Even if the knowledge is already known by the group as a whole, it may be useful to consolidate the information.

Fundamentally this process tries to answer the question, ”What do I need to know in order to create x result”. Where x is the goal of the component as a whole, or x is a subgoal which is thought to contribute to the overall goal of the component. This phase of testing sets the theorized design against existing knowledge. Often times it is necessary to return to the theorizing phase and reconstitute the design given new information which has been acquired.

Acquiring components phase has analogs in both hardware and software domains. In the software domain, acquiring components consists of software packages, such a Apache 2, or knowledge assets necessary to complete a program. In the case of this project, we needed to learn how to use and configure apache, write Python code on the Raspberry Pi, use py-spi in order to communicate with the Minigen, and use GPIO library on Raspberry Pi to communicate with the PGA components.

Compare this to the hardware domain where the acquisition of components is fairly straightforward. Components are necessary to be purchased. This process takes much longer when compared to downloading a software package. Thus, it is useful,

wise, and resource efficient to spend much more time in the theorizing a design phase. Having an increased degree of certainty that a given component will preform as expected alleviates the time and money required to determine that a component will not work empirically. This certainty can be developed though simulations, or developing a mathematical description of the output of a design.

6.1.3 Implement design

Of all the phases, this phase constitutes the largest investment. The majority of time spent on the project is used to implement a design. The goal of this phase is both obvious and complex.

An increased degree of efficiency may be achieved by constructing a minimal working example(MWE). The benefit in doing this is twofold. First, a MWE is often easier to construct compared to a version which is constructed into the other components of the project. Second, because constructing a MWE requires that this sample implementation not be integrated into the rest of the project, issues which arise from the interplay between devices are not present. This helps to isolate issues which are a product of the specific aspect of the project which is being implemented.

Implementing designs in hardware is significantly different compared to software. Hardware designs must be constructed with physical components on a breadboard. These components must be connected and measured with lab equipment in order to determine if the components are having the correct output. All the steps in this process take time. Other issues also exist due to the physical nature of hardware components. A component might be partially burned out and providing output which is not correct, but still proving output. The difficulty with this is that the component appears the same as it would if it were connected incorrectly. For these reasons, the Implementing a design phase consumes many more resources in the time and economic domains compared to software implementations.

6.1.4 Understand problems

After implementation of the design is complete, it must be determined whether or not the device functions as expected. Often times this means looking at the input and output waveforms on an oscilloscope for hardware or observing the change in state of the GPIO pins for testing software. Once a problem has been identified, the source of the problem must be located.

To clarify the above point, consider an example of a problem which might be observed is a difference in amplitude of the output waveform compared to what was expected. The problem might be any component which is connected to the measured point. This includes components which are connected via other components.

Often times to identify the source of an issue, it is necessary to understand what should be the input and output of all components in the circuit. Testing the inputs and outputs of each component in turn moving away from the originally observed wrong output can help to find where the origin of the problem occurred. Perhaps the component which gives input the component previous the the component with the observed problem is connected incorrectly. This could cause the output of all future components to become incorrect.

A similarity between debugging code and finding issues in hardware implementations is the effect of mistakes. The way a mistake propagates though a program is similar to the way mistakes propagate though hardware implementations. All events after the first error are often a result of the first error. There fore these events are also in error. Often times a good debugging strategy is to approach solving the first error. The benefit in doing this is that future errors might be solved indirectly.

6.1.5 Return to step 1

Many times it is found that designs would not work and thus this process is reset to the beginning. This step can be disheartening, but it is wholly necessary. Emotions of anguish may cloud a person's judgment causing them to stick with a particular implementation for far longer than what is necessary to determine better solutions exist. Developing a control over these emotions yields decisions which reduce the time taken to complete a project and often produce better results.

Much wisdom is needed to be able to objectively evaluate one's current situation and determine whether it is advisable to continue down the current path or whether The new information gathered in the "understanding problems" phase warrants the construction of a new design or significant portion of design. Often times this can be reduced to answering the following question honestly, "Given what is now known, is it wise to invest in the current course of action, or is there something else which might have an improved probability of success"

In software, returning to theorizing a consumes far fewer resources compared to redesigning a hardware implementation. In software, new packages may be downloaded nearly instantaneously. Compare this with hardware where new components must be chosen, bought, and shipped. The need to redesign can be expensive and time consuming, but often times it is wise to do if the current design is not working as expected to such an extent that another design would be a smarter investment.

6.2 Testing Results

Testing occurred in an iterative process as described above throughout the semester. Each time a new design would be reached, the steps above were used to uncover what the issues were, how to solve them, and whether it was wise to solve them at all. The alternative to solving current issues is establishing a new design.

A typical testing environment includes:

- Oscilloscope
- Raspberry Pi
  - Connected for monitor for web interface access
  - Connected to circuit to control Minigen, PGA's
- Multiple breadboards
  - Minigen Function Generator
  - PGA's
  - Summing amplifier

6.2.1 Known Issues

Below are some of the issues found through the course of our testing which have not been resolved. These issues are fairly minor compared to the overall functionality.

The current solution has some noteworthy issues which need to be addressed. Issues are defined as unintended issues of unknown origin. Possible reasons for each of the issues are discussed as well as the accommodations made in this implementation to lessen their impact. Potential solutions are also mentioned.

B23

In the current prototype, there is an ongoing issue with the Minigen Function Generator. This device works as expected in most cases. The exception occurs when bit 23 of either frequency register is set high. This case will cause the Minigen device to produce a $4Mhz$ sine wave. There is potential that the specific Minigen device used is responsible for this bug. Further testing is required.

The solution currently implemented is to detect conditions which will cause the error and avert these situations problematically. Whenever bit 23 is set to high in a frequency register write, the current implementation sets bit 23 to low and sets all less significant bits to high.

Current Draw from Raspberry Pi

Throughout the course of our testing, the Raspberry Pi turned off at random several times. After this happened in a few different scenarios, it was determined that this problem did occur when an active display adapter was used and did not happen when a passive adapter was used to connect the display. The difference between these adapter types is, active adapters require power while, passive adapters do not. The question becomes, "what about requiring more power from the Raspberry Pi creates issues?".

After doing some research on the Internet, we found several sources which describe a relevant protection mechanism of the Raspberry Pi. When there is more power demanded from the Pi than the Pi can supply then the Raspberry Pi will turn off to protect itself. This is a useful mechanism and must have saved our test Raspberry Pi a dozen times.

The amount of power this implementation requires from the Raspberry Pi is somewhat high. The $3.3V$ output rails are used to power the Minigen Function Generator, and other GPIO pins are also used for interacting with the PGA's. Given these conditions, it is not surprising that the Rasberry Pi protection mechanism was necessary when additional power was required through the Pi's HDMI port.

Amplifier Circuit

Currently, the amplifier circuit is not capable of reaching the maximum frequency or voltage requirement. Currently the maximum achievable frequency at which the voltage gain of the circuit has not dropped by more than $3db$ from it's intended value is around $800Khz$. In other words the $-3db$ frequency of this circuit is $800Khz$. The issue which prevented reaching a frequency of $1Mhz$ was an insufficient gain bandwidth product of our chosen op-amp.

The maximum voltage can also not be reached. This is due to an insufficient slew rate of the OPA552, the current op-amp. This op-amp is unable to change voltage fast enough to output large amplitude waves at high frequency.

6.2.2 Possible Solutions

In the case of the current draw from the Raspberry Pi problem and the B23 bug, it is clear how the problem might be solved. However, in the case of the amplifier circuit the solution is non-obvious. Possible remedies could range anywhere from a complete redesign to the purchase of additional components. The later option is more resource efficient if it is available. There much more expensive op-amp around $150 has the necessary specifications to fulfill the project requirements. The part number of this op-amp is 598-1449-ND. Replacing the OPA552, the current op-amp, with this one would, in theory, allow the design to meet all the frequency and voltage requirements.

7 Concluding Remarks

At the onset of this project, there was a lot of rapid success. During the first semester, much of the scripts which interact with the circuit from the Raspberry Pi were written. We were able to modify the frequency and communicate with the PGA's by the end of the first semester. The work on the amplification portion of the project took significantly more time. Most of this additional time expense came as a direct result of the number of problems encountered.

In addition to the implementation struggles in the second semester of this design experience came a shortage of manpower. One group member had to drop out of school for financial reasons. This was especially difficult to deal with as the number of people on the project was already fewer compared to the number called for in the project description. This project originally specified that there should be three computer engineers and three electrical engineers working on the project. Reality instead afforded the group assigned to this project four computer engineers. This eventually became three computer engineers.

Being computer engineers, our skill set lies outside the realm of complicated circuits. Our lack of experience with building and testing circuits designs manifested itself in the struggles constructing the multi-stage amplifier circuit. While the general lack of expertise with the circuit components of the project hampered our group significantly in the completion of the project, it was a very good learning experience. Often times the most difficult situations inspire the most growth.

The final state of the project is very close the the design specifications. The state does deviate in a few key aspects, but overall the viability of the design has been proven. If the more expensive op-amps would have been purchased, all of the design parameters would have been met, at least in theory. In other words, the limitations of the current implementation are due to op-amps with insufficient slew rate and gain-bandwidth product.

Many of the issues which arose in this project came from the amplifier circuit. There were many design iterations where a new component would get introduced. This component would always cause some problem or have an adverse effect in some way. Eventually the component would be removed, or the design would be modified to accommodate the problems associated with the new component. Sometimes the design would even

be reverted to a previous configuration. Progress on the amplifier circuit came in small increments. Over time, these increments summed to the nearly-functioning implementation at the conclusion of this project.

A Operation Manual

A.1 Quick Setup

Here are listed the setup steps as succinctly as possible. If more detail is required, the below Setup section covers each step in more detail.

1. sudo raspi-config
   (a) expand file system
   (b) enable SPI in advanced options
   (c) (optional) enable SSH in advanced options
   (d) Finish ¿ Reboot
2. Acquire Project Codes
   (a) git clone http://github.com/timdee/cpre492
3. Modify apache2 document directory
   (a) sudo rm -r /var/www
   (b) sudo ln -s /home/pi/cpre492/www /var/www
4. Enable cgi-bin
   (a) sudo a2enmod cgi
5. Modify cgi-bin Directory
   (a) sudo rm -r cgi-bin /usr/lib/cgi-bin
   (b) sudo ln -s /home/pi/cpre492/cgi-bin /usr/lib/cgi-bin
6. Modify apache to run as user pi
   (a) sudo nano /etc/apache2/envvars
   (b) export APACHE_RUN_USER=pi
   (c) export APACHE_RUN_GROUP=pi
7. sudo reboot

A.2 Setup

This section details the materials needed and how to set them up. This section assumes you have nothing other than the circuit to connect to the Raspberry Pi and the controlling code which needs to be placed on the Raspberry Pi.

Setup includes all necessary information for the Raspberry Pi configuration. Such information is provided for the purpose of understanding how the system has been established in hopes that it might be easier to modify or change in the future.

Steps:

1. Purchase a Raspberry Pi
   (a) micro SD card
   (b) micro USB power cord
   (c) (optional) USB wifi adapter
   (d) (optional) Ethernet cable
2. Install Rasbian Linux Operating System on Raspberry Pi
3. Configure Installation
4. Place circuit controlling software on the Raspberry Pi
5. Install software packages on Raspberry Pi
   (a) Apache 2 Web Server
   (b) RPi.GPIO
   (c) spidev
6. Modify configuration files on the Raspberry Pi
7. Verify configuration

A.2.1 Purchase a Raspberry Pi

The object of this step is self-explanatory, however, there are some useful points to note when purchasing a Raspberry Pi. Often times the Raspberry Pi is not sold with any accessories. This means a few additional items must be purchased in order run and use the device. The additional items which must be purchased are: a power cord and micro SD card.

A.2.2 Install Rasbian Linux Operating System on Raspberry Pi

It is recommended that Rasbian Linux distribution is used as the operating system for the Raspberry Pi. This system will work with other operating systems, but Rasbian has many of the necessary libraries available at install. In addition, Rasbian is optimized for the hardware of the Raspberry Pi. Other distributions may run slower, or not have all of the correct drivers at installation. There are no current factors which would motivate the use of another distribution.

The latest version of Rasbian can be downloaded from: `https://www.raspberrypi.org/`

This website also has a lot of good documentation for the Raspberry Pi. It can be a useful resource for troubleshooting issues. For this purpose, there are many guides provided.

One such guide describes how to install Rasbian to the Raspberry Pi. This guide can be viewed here: `https://www.raspberrypi.org/learning/noobs-install/`

The previous guide describes the process of installing the operating system with NOOBS. Another way to install Rasbian could be as follows:

1. Acquire a micro SD card
2. Download Rasbian Linux Operating System
3. Acquire a program capable of writing an image to a micro SD card on a computer with a micro SD card interface
4. Write the image to the micro SD card
5. Place the micro SD card in the Raspberry Pi
6. Power on the Raspberry Pi and complete configuration

In general, the processes can be summarized as writing an image of the Rasbian Linux Operating System to an SD card. While this brief description does not capture the nuances associated with installation, it is enough to understand the correct course of action.

Interfacing With the Pi During the setup process, there will be need to interact with the Raspberry Pi. This can be done in a couple ways. One way to interface with the Pi is to use it directly. Direct use can be done by using the HDMI output on the Raspberry Pi to input to a monitor. A keyboard an mouse may also be inserted into the USB ports on the Raspberry Pi. Interactions using this method are similar to using a standard desktop computer.

Another useful way to interact with the Raspberry Pi might be to use the secure shell program (SSH). SSH allows remote communication with the Pi as long as it is on the same network. An example of how this might work is this, plug the power cord and Ethernet cable into the Raspberry Pi, after the Pi has booted fully, another computer runs the following command.

```
1 ssh [raspberry pi ip address]
```

After running this command, the user will be present with a login prompt. After login is complete, a command prompt will be displayed. This will enable the user to interact with the pi as if the interaction was direct while still being connected to the Pi over the network.

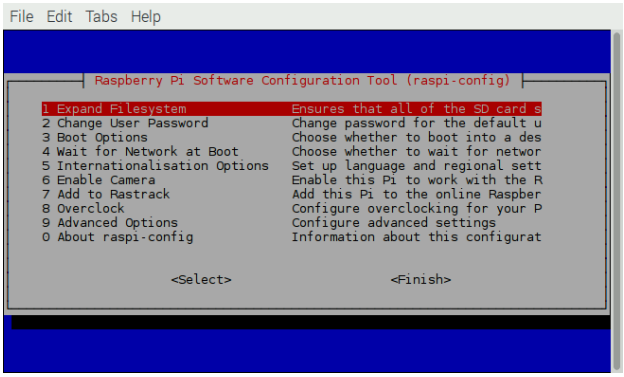
A.2.3 Configure Installation

It is necessary to configure the installation for two reasons. First, when the installation material was written to the installation medium, it's partition was only exactly the size it needed to be in order to preform the install. In order to put additional files on the system, the file system must be expanded. Second, this project utilizes the SPI interface on the Raspberry Pi. In order to use this interface, SPI module needs to be enabled.

Thankfully Rasbian Operating system provides an easy setup script for preforming both of these actions. To run this setup script in order to configure the installation, the following command can be executed as user Pi.

```
1 [pi@raspberrypi ~]$ sudo raspi-config
```

The following screen should present itself after running the above command.



Follow the prompts in order to expand the file system. To enable SPI, it is necessary to first select "advanced options" followed by "enable SPI". Optionally, SSH may be enable. Enabling this option will cause an SSH server to be run on the Pi after the next reboot. Make sure to reboot; acquiring program code in the next step will require that the file system has been expanded.

A.2.4 Place circuit controlling software on the Raspberry Pi

In order to acquire the project code constructed to allow the Raspberry Pi to control the rest of the circuit, the following command may be used. This command should be run in user pi's home directory, "/home/pi". The rest of the guide assumes this location for the files. If this is not the chosen location on the Raspberry Pi, simply use the chosen location in place of "/home-/pi".

```
1 git clone http://github.com/timdee/cpre492
```

This command will download the code from a github repository. There should now be a folder "/home/pi/cpre492" with all of the code and documents present. If an error occurs which indicates there is no more disk space, then it is likely that rebooting the Raspberry Pi will fix this issue.

A.2.5 Install software packages on Raspberry Pi

In order for the software written to control the circuit to preform it's task, a few additional software packages must be installed. These packages are necessary for: running the web server and modifying the values of the GPIO pins. The names of the packages are as follows

- apache2
- spidev
- RPi.GPIO

In order to install the packages, it is necessary to run the following command:

```
1 sudo apt-get install [package name] -y
```

The above command will install the desired package. This may be done for apache as follows:

```
1 sudo apt-get apache2 -y
```

Note, RPi.GPIO is usually installed with the installation medium. If it is not, the process for installing RPi.GPIO is slightly different. The package must first be downloaded from: `https://pypi.python.org/pypi/RPi.GPIO`

After the package has been downloaded, it needs to be extracted and moved to the the cgi-bin directory of the apache web server. Such a process might look like the following:

```
1 [pi@raspberrypi ~]$ cd Downloads
2 [pi@raspberrypi Downloads]$ tar -zxvf RPi.
    GPIO.tar.gz
3 [pi@raspberrypi Downloads]$ mv RPi.GPIO ~/
    apache2/path/cgi-bin/
```

The process outlined above may not be necessary if RPi.GPIO is included in the provided softwares. If this is the case, then the above procedure may still be useful for updating the library. This may be necessary to fix unforeseen, obscure bugs.

A possibly old version of spidev is included with the provided codes. If an upgrade is required, the process for doing so is similar to RPi.GPIO process. The only difference being the package will be downloaded from a different place.

A.2.6 Modify configuration files on the Raspberry Pi

The configuration files which need to be modified are related to Apache 2 web server. The files which need to be modified for the following reasons. First, the apache user (www-data) does not have the permissions necessary to run some of the library functionalities. One solution to this issues is to run apache as a

user which does have permissions. In this case, we choose to use the default user, pi for this purpose.

Second, the apache package needs to be told where the files for the web server have been placed, otherwise apache will load the default configuration which is not what is wanted. This is another simple modification to one of the configuration files There is, however, an alternative to modifying the configuration of the server in specifying the directory where the web server files are located. The alternative is to create symbolic links at the default locations loaded by the web server. This option is chosen for compatibility purposes. Taking the former approach assumes the configuration files will be setup the same with every iteration of apache2. This is not always the case.

Running Apache as User pi To change the run user for apache, run the following command.

```
1 [pi@raspberrypi ~]$ cd Downloads
```

This will initiate a command-line text editor which should be used to modify the APACHE_RUN_USER and APACHE_RUN_GROUP to be the following:

```
1 APACHE_RUN_USER = pi
2 APACHE_RUN_GROUP = pi
```

Modifying Web Site Files Location There are two relevant directories, *www* and *cgi-bin*. The method chosen to modify these directories are though the creation of symbolic links at the default file locations. This may be accomplished though the following command sequence:

```
1 [pi@raspberrypi ~]$ sudo rm -r /var/www
2 [pi@raspberrypi ~]$ sudo ln -s /home/pi/
      cpre492/www /var/www
3 [pi@raspberrypi ~]$ sudo rm -r /usr/lib/
      cgi-bin
4 [pi@raspberrypi ~]$ sudo ln -s /home/pi/
      cpre492/cgi-bin /usr/lib/cgi-bin
```

A.2.7 Verify Configuration

In order to verify that the configuration is working properly, open a web browser, type localhost in the navigation bar, and press enter. If a web interface used to update voltage and frequency values is loaded then the configuration is correct.

A.3 Demo

This section details the process by which a device which has already been setup may be showcased. An example use of the system might be as follows. Connect the output of the circuit to the pair of capacitive plates which will drive the dielectrophoresis experiment. Once connected, Connect to the raspberry pi over the local area network from any computer on the network and use the interface to modify the voltage and frequency output of the circuit.

Steps:

1. Power on the Raspberry Pi
2. Connect the Raspberry Pi to the network
3. The output of the circuit should connect to capacitive plates used for dielectrophoresis
4. Acquire the IP address of the Raspberry Pi
5. Enter the IP address in the navigation bar of a web browser
6. Input the desired voltage and frequency values and click update
7. The output of the circuit can be seen to change to the desired values

A.3.1 Power on the Raspberry Pi

In order to power on the Raspberry Pi, It must be plugged into a wall output. The power adapter for this device is the same as any micro USB smart phone adapter. Once plugged in, The Raspberry Pi will power up automatically.

If the Raspberry Pi is connected to a monitor, there should be many lines of output to the screen. The powering on process takes about a minute, so be patient. After startup has completed, one of two scenarios will be the case. Scenario 1, the Pi boots to a graphical user interface. If this is the case, then continue with the succeeding steps.

If however, there is a command line displayed instead, this is scenario 2. In scenario 2 it is necessary to log into the pi. This may be done with the default user name and password listed below.

```
1 # username: pi
2 # password: raspberry
```

A.3.2 Connect the Raspberry Pi to the network

Connecting the Raspberry Pi to the network may be done in a couple of way: through the Ethernet port on the Raspberry Pi, or through a wireless network adapter connected to one of the Raspberry Pi's USB ports. Either method of connection will allow any computer on the local network to connect to the web server running on the Raspberry Pi.

A.3.3 The output of the circuit should connect to capacitive plates used for dielectrophoresis

Ensure all of the outputs to the circuit are connected properly. Preforming this step incorrectly can cause damage to the equipment.

A.3.4 Acquire the IP address of the Raspberry Pi

Finding the Raspberry pi on the network can be somewhat tricky. The Raspberry Pi has a display output on board. If access to this display is available, a keyboard may be connected to the pi in order to interact with it.

To acquire the IP address of the Raspberry Pi, login and run the 'hostname' command with arguments '-i'. This command is depicted below.

```
1 # hostname -i
```

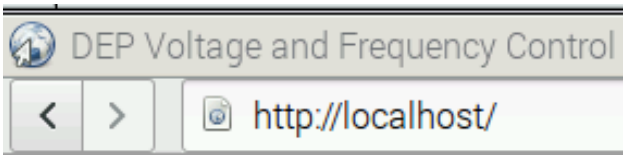
The output of this command will the the IP address of the Raspberry Pi on the network. Note the raspberry pi may be configured to login automatically at start up. This depends on the installation medium.

There are other ways to acquire the IP address which involve scanning the network from another computer on the network. Another way would be to configure a static IP address for the Raspberry Pi.

Configuring a static IP can be done in a few ways. One way to accomplish this is to modify the router setup to assign the Raspberry PI a specific IP. Another method is to configure the PI to request a specific IP address.

A.3.5 Enter the IP address in the navigation bar of a web browser

On any computer connected to the same network as the Raspberry Pi, open a web browser. In the navigation bar of this browser, enter the IP address retrieved from the 'hostname' utility. In the below example, The web browser is instructed to navigate to localhost. This can be used to access a web server running on the current machine. If the goal is to navigate to a web server running on a different machine, thee entering the IP address of this machine in place of localhost will accomplish this goal.



A.3.6 Input the desired voltage and frequency values and click update

The web interface contains fields to input the desired frequency and voltage values. Enter these values and click the 'update' button. Doing so will cause scripts to Run on the Raspberry Pi that set the values of the GPIO pins in such a way that the output is produced by the circuit. There is also a Radio Button group which will allow the output waveform to be modified among triangle, square, and sine.

A.3.7 The output of the circuit can be seen to change to the desired values

After the 'update' button is pressed, the output of the circuit will be modified to the closest possible values. The voltage and frequency resolution are limited, thus the output may not be exactly the value entered.

After update is pressed, the web interface will be redisplayed. This will allow the modification of voltage and frequency again.

B Initial Designs

This section covers the designs that have been tried throughout the course of the project. These were problems with each of these designs which motivated a change from that design to a more resent design. Designs are presented in roughly chronological order in each section to perhaps make it more clear what motivated a particular design choice. Each component underwent various adaptations over the duration of the project.

In an introductory economics class, it is common that students are taught about sunk costs. Sunk costs refer to those costs which have already been incurred and cannot be recovered. These classes teach that suck costs should not be considered in making future investments. In other words, one should not ask themselves the extent of current investment down a particular path. Rather, one should ask, given what is known now, which investment is more intelligent.

While economics classes teach about sunk costs in the context of monetary investment, the same logic may be applied to other domains. In the case of this project, the investment capital is time and energy. Regardless of how much energy has been invested in a particular design, it is necessary to evaluate alternatives to that design. If these alternatives than look better given what is known about both designs than the design should be modified accordingly to fit the alternative design.

Throughout the course of this project, several components needed to be redesigned. Below is some mention of these designs and the issues encountered which motivated deviation from them.

B.1 Frequency Control

The Raspberry pi is capable of producing square waves by turning the GPIO pins on and off rapidly. We can use this functionality to produce a wave of the frequency indicated by the user. The GPIO pins can also be used to set the voltage by communicating with the circuit how much the output waveform should be amplified. The downside to this approach is the analog circuit component will need to be more complex. The analog circuit needs to output a sine wave. With this approach we would need to integrate the square wave produced by the GPIO pin.

There exist alternatives to using the GPIO pins to generate a signal with a given frequency. We could instead use the GPIO pins on the raspberry pi to communicate with a small signal generator, such as *sparkfun.com*s Minigen Function Generator. This would make programming the Raspberry pi more complex, but could lead to higher quality waveforms. Producing a sine wave using the Minigen signal generator is likely to to produce fewer distortions compared to integrating a square wave produced by the RPIs GPIO pin twice.

This design was scrapped due to the increased complexity of programming on the Raspberry pi in conjunction with concerns about the maximum amount of current which could be output by the Raspberry Pi. These concerns in conjunction with the ease of SPI communications with the Minigen drove the choice to use the Minigen to generate the frequency of the output.

B.2 Voltage Control

B.2.1 Digital Potentiometer

The output of the digital potentiometer has 128 steps. This Translates into our ability to set 128 different gains on our amplifier. We will need multiple stages of amplifier to go between 1 and 60 Vpp. The most prominent reason for this is due to the gain bandwidth of the op-amps. We will not be able to have a large gain while still producing a frequency of 1Mhz.

One problem we foresee with the digital potentiometer is that it cannot handle a large amount of power. This may force us to come up with different amplifier configurations, or use the digital potentiometer in a different way. Another way we could possibly use this device is as an attenuator at the input to the amplifier.

Another problem which might arise with the digital potentiometer is the capacitance of the wiper. We dont have any context for understanding how much this will affect the output signal. According to some preliminary calculations, we have determined that the capacitance will not present a large problem. This design was replaced by a programmable gain amplifier.

B.2.2 Transistor switch

The overall voltage output by the amplifier circuit varies between $1V_{pp}$ to $60V_{pp}$. In our implementation, this range is segmented into three parts of $20V_{pp}$ each. Each of the three segments are input to a summing amp to create up to $60V_{pp}$ overall.

A PGA is used for fine adjustment of one $20V_{pp}$ range while the other two ranges are either $20V_{pp}$ or $0V_{pp}$. In other words, there ranges are turned on or off.

The original design for turning on and off the ranges required that a BJT transistor switch circuit be used. The intent was for this circuit to have either $20V_{pp}$ or $0V_{pp}$ depending on a GPIO pin from the Raspberry Pi. This design did not work as intended. Even when the transistors were off there was still current leakage. This current leakage caused problems when input to the summing amplifier. For this reason, the BJT transistor switch ciruits were replaced with solid state relays.

B.2.3 Relay

The proposed use for the relays was similar to the to the transistor switch. The advantage the relays have is the use of an internal led to allow or disallow current though the relay. One way this might work is by connecting a GPIO pin from the Raspberry Pi to the led pin on the relay. Setting this GPIO pin to high would then cause the led to shine allowing the signal from the Minigen to flow through the relay.

The overall voltage range, $1V_{pp}$ to $60V_{pp}$, is divided into three $20V_{pp}$ ranges. The relay's have two states, on and off, which allow for moment between the ranges. When on, the input the the Amplifier circuit is amplified to $20V_{pp}$. This $20V_{pp}$ signal is input to the summing amplifier. There are two of these relay circuits used. Turning them on or off allows the voltage range to be chosen. These relay circuits are controlled by GPIO pins on the Raspberry Pi.

The problem which occurred with this solution was that the relays were incapable of operating at the desired frequency. The

relays began to have problems at only $25K_{hz}$. Compare this to the required $1M_{hz}$ frequency, and it is obvious that the relays are not a good solution.

B.3 Amplification Stages

The initial design for the amplification stages utilized three stages. Two of these stages were used to increase the voltage by a constant amount while the third stage is used to adjust the voltage within the range. This give the variability of one pga multiplied by the number of stages, in this case three were used.

There are three $20V_{pp}$ voltage ranges. Which range being acted in is chosen by the relay circuits. Within a given range, however, a PGA is used to control the voltage output. In our implementation, a PGA has control over a $20V_{pp}$ range. The PGA has 8 steps within this range. This Device is controlled by the SPI interface on the Raspberry Pi.

The problem with this design which motivated change was the switches used to increase the voltage by $20V_{pp}$ would introduce noise into the signal. Another issue with this design was that it used the PGA's in a very limited way. Theoretically, if all PGA steps were able to be used for each step of the other PGA's this gives $3^7 = 343$ steps. This means we have reduced the number of possible steps by a factor of 49 in order to accomplish this design; better implementations must exist.

C Other Considerations

An argument can be made that there cannot be a truly accurate model of life. Any such model with an infinite degree of accuracy would need to contain the model of life within it. And that model would then need to contain the model of the model. This is scenario is impossible and illustrates why it is necessary to develop simplified models.

Every model is based in reality, but the model is not reality. Sometimes simplifications are made in the construction of the model which mask some of the issues which can arise if it turns out this simplification was not valid in the use scenario.

The project description for this industry project determined it was advisable for the group working on it to have three computer engineers and three electrical engineers. Instead, our original group consisted of four computer engineers. After the first semester of this project, one of our group members dropped leaving only three computer engineers. As a group we were able to accomplish most of the goals for the project. Especially the goals more central to the topics covered in the undergraduate computer engineering work at Iowa State University.

The fundamental issue with the portions of the project more suited to an electrical engineer is our models are oversimplifications of the physical circuit components. Being unable to model the circuit accurately at the design phase led to a lot of unnecessary implementation time. Where this is a lot of experiential learning in such a process there is also great expense in the time domain. This coupled with a lack of advanced knowledge about circuits in general led our group the have a tough time with the circuits component.

One instance where our group's oversimplification of components hampered progress was in the design of the amplification portion of the circuit. We originally intended that the amplification would happen in three stages. The op-amp chosen to preform the amplification turned out to only work for gains greater than 5 unless capacitors were used to connect the inverting input and output to ground. A capacitor also needed to be used in the feedback loop. We need a gain slightly over unity, thus the use of this is necessary. These capacitors did indeed make the op-amp work at the gain we need, but they have the adverse effect of turning the op-amp into a filter and applying a phase shift the the output of the op-amp.

This scenario presented us with a choice, either abandon the current op-amp, or try to design all the stages such that the cutoff frequency is greater than $1M_{hz}$ with a phase shift equal to the other stages. Given that we couldn't find any other op-amps in our price range which met the slew-rate, bandwidth, and voltage rail requirements of our project, the later was chosen. This made designing the stages significantly more difficult. For this reason we decided to only use two stages as this would be easier to match up precisely. With three stages it would be very difficult to create a uniform phase shift among the stages. This would make it difficult to produce a precise output voltage.

Even though the goal was known, to design two amplifiers with different gains having equal phase shifts, accomplishing this was not trivial for us. Our group did not understand how to model this circuit. Knowing this would allow us to change components in order to modify the phase shift without changing the gain. Eventually we found that if, in the feedback loop, we increased the value of the resistor by the same factor which we reduced the capacitor by we could produce a gain given by $\frac{R_F}{R_{IN}}$ while maintaining a phase shift.

Many issues throughout the semester arose due to general lack of knowledge about circuits. One of the clearest examples of this is occurred in the interactions among components. We did no understand how to separate components initially. This led to scenarios where the input, output of two components could work perfectly, but when these components were connected in series the output of the overall circuit did not work as expected.

The lack of experience also manifested in the amount of time it would take for us to debug "simple" circuit problems. We would, for instance, see an odd wave on the oscilloscope which might clearly indicate there wasn't a common ground or that the power supply wasn't turned on (oops). Not knowing this, we would proceed to the next logical step, staring at the circuit for exorbitant amounts of time and checking all the connections. Eventually we learned what certain types of oscilloscope traces might imply about the problem, but experience would have made this process much faster.

D Code

Listing 1: Bash script used to evoke GPIO library

```
#! /bin/bash

# open python thing
cd /home/pi/cpre492/cgi-bin

echo -e "import pga\np_amp=pga.pga($2, $3, $4)\np_amp.setGain($1)" | sudo python
#sudo python import pga
#sudo python p_amp = pga.pga($2, $3, $4)
#sudo python p_amp.setGain(-1)
```

Listing 2: Update Website Script

```
#! /usr/bin/python2.7

import cgi
import cgitb
import update_voltage_frequency

def print_file(file_name):
    with open(file_name, 'r') as file:
        line = file.readline()

        while line:
            #print "\""+line+"\""
            print line
            line = file.readline()

# create instance of field storage to get values
parameters = cgi.FieldStorage()

# get the data from the fields
#update_voltage = parameters.getvalue('update_voltage')
#update_frequency = parameters.getvalue('update_frequency')

voltage_value = parameters.getvalue('voltage')
frequency_value = parameters.getvalue('frequency')

# Update the frequency and voltage
update_voltage_frequency.update_voltage(voltage_value)
update_voltage_frequency.update_frequency(frequency_value)

# This script is designed to count as a test
print "Content-type:text/html\r\n\r\n"
#print "<html>"
#print "<head>"
#print "<title>CGI-Update-Procedure</title>"
#print "<head>"
#print "<body>"
#print "<h1>Current Values:</h1>"
#print "<h3>Voltage: %s V</h3>" % (voltage_value)
#print "<h3>Frequency: %s Khz</h3>" % (frequency_value)
```

```
#print "</body>"
#print "</html>"

# print out css to be applied
print '<link href="/html/css/bootstrap.min.css" rel="stylesheet" type="text/css">'
print '<link href="/html/css/bootstrap-theme.min.css" rel="stylesheet" type="text/css">'
#print_file('/home/pi/cpre492/www/html/css/bootstrap.min.css')
#print_file('/home/pi/cpre492/www/html/css/bootstrap-theme.min.css')

# Reprint index.html so that the user may change the voltage again
print_file('/home/pi/cpre492/www/html/index.html')
```

Listing 3: Update Voltage and Frequency Script

```
#! /usr/bin/python2.7

import spidev
import minigen
import subprocess
import math

#Designed to communicate with a Minigen connected to the GPIO pins
spi = spidev.SpiDev()

# Test function
def main():
  print 'running in test mode'

  # Test setting the frequency using spi
  update_frequency(30)

  # Test setting the voltage
  update_voltage("3")

# Update the voltage level to the specified value.
# This is not the voltage output by the minigen,
# Instead it is the voltage output by the circuit as a whole.
def update_voltage(voltage):
  # determine the values for the two pga's based on the voltage
  ##pga_0 has amplifier of 7.5 gain after it
  ##pga_1 has amplifier of 1 gain after it
  amp_gain_0 = 7.5;
  amp_gain_1 = 1.0;

  ##compute voltage values
  pga_voltage = int(voltage)

  ##pga voltages
  pga_0_gain = math.floor(pga_voltage / amp_gain_0);
  pga_1_voltage = pga_voltage - pga_0_gain * amp_gain_0;

  ##pga gains
  ##pga_0_gain = pga_0_voltage / amp_gain_0;
  pga_1_gain = pga_1_voltage / amp_gain_1;

```

```
    #TEST PRINTS FOR 2 STAGE AMPLIFIER
    #print "pga_voltage " + str(pga_voltage)

    #print "pga_0_voltage " + str(pga_0_voltage)
    #print "pga_1_voltage " + str(pga_1_voltage)

    #print "pga_0_gain " + str(pga_0_gain)
    #print "pga_1_gain " + str(pga_1_gain)

    #print "pga_0_gain_script " + str(int(round(-1*pga_0_gain)))
    #print "pga_1_gain_script " + str(int(round(-1*pga_1_gain)))

    # call a script that will set the pga values
    # be able to choose pga pins set based on this call
    subprocess.call("./pga_calling_script.bash " + str(int(round(-1*pga_0_gain))) + " 5 6 13", shell=True)
    subprocess.call("./pga_calling_script.bash " + str(int(round(-1*pga_1_gain))) + " 4 17 27", shell=True)

# Update the frequency to the specified value. Values are given in Khz.
def update_frequency(frequency):
    # make an instance of the minigen class to handle the connection
    m = minigen.minigen()

    # ask the minigen to set the new frequency
    m.setFrequency(float(frequency)*1000)

    #close the conection
    m.close()

if(__name__ == "__main__"):
    main()
```

Listing 4: Minigen Control Script

```
#! /usr/bin/python2.7

import spidev
import time
import sys
# Designed to provide some of the functionality from SparkFun_MiniGen.cpp
# designed so that you only need to use set_frequency to set the frequency
class minigen:
  # initialize the connection with the minigen
  def __init__(self):
    self.spi = spidev.SpiDev()

    # open(bus, device)
    self.spi.open(0, 0)

    # minigen is driven at 40Mhz
    #self.spi.max_speed_hz = 15000000

    self.controlReg = [False]* 16
    self.controlReg[16-13] = True
```

```
21
22      self.freqReg0 = [False]*32
23      self.freqReg1 = [False]*32
24
25      self.freqReg0[31-30] = True
26      self.freqReg0[31-14] = True
27
28      self.freqReg1[31-31] = True
29      self.freqReg1[31-15] = True
30
31      self.fudgeFactor = 1
32
33  ##########      Control Register 16Bits
34  #   Bit Number    Name    Function
35  #   D15           Addr1     Always 0        D15 and D14 is the address of the control
        register
36  #   D14           Addr0     Always 0
37  #   D13           B28       When 1: allows a complete word to be loaded into a freq reg with
        two consecutive write. First contains 14 LSB, second contains
38  #                           14 MSB. (First two bits is freq reg addr) Consecutive writes to
        the same freq register is not allowed, you must alternate.
39  #                           When 0: Configures the 28bit freq reg is act as two 14 bit regs.
        One contains 14 LSB, the other 14MSB. This allows for coarse, or fine
40  #                           grain tuning. HLB defines which to change.
41  #
42  #
43  #
44  #   D12           HLB       This allows the user to continiously load the MSB or LSB of a
        freq reg. Ignoring ther other 14 bits. When B28 = 1, this is ignored.
45  #                           When 1: Allows write to 14 MSB
46  #                           When 0: Allows write to 14 LSB
47  #
48  #
49  #
50  #   D11           FSEL      Selects either freq0 or freq1
51  #   D10           PSEL      Selects either phase0 or phase1
52  #   D09         reserved      0
53  #   D08         RESET     When 1: resets internal regs to 0. When 0: disables the reset
        function.
54  #   D07         Sleep1    Enables or disables MCLK
55  #   D06         Sleep12   Powers down on chip DAC
56  #   D05         OPBITEN   0
57  #   D04                   0
58  #   D03
59  #   D02           TODO
60  #   D01
61  #   D00
62
63    def chooseFreq0(self):
64      self.controlReg[15-11] = False
65    def chooseFreq1(self):
66      self.controlReg[15-11] = True
67    def enableB28(self):
68      self.controlReg[15-13] = True
```

```
69    def disableB28(self):
70      self.controlReg[15-13] = False
71    def enableHLB(self):
72      self.controlReg[15-12] = True
73    def disableHLB(self):
74      self.controlReg[15-12] = False
75
76    def sendControlReg(self):
77      controlRegNum = self.boolListToInteger(self.controlReg)
78      self.spi.xfer([controlRegNum >> 8, controlRegNum & 0xFF])
79
80    def getControlReg(self):
81      return (self.boolListToInteger(self.controlReg))
82
83
84    #Frequency Functions
85    #
86    #Frequency Registers are set up as one 1 32bit register with [31-30] and [15-14] defined
          to be the address
87    #
88
89    def setFreqRegister(self,freqReg, isMSB, num):
90      if(num > 0x3FFF):
91        return -1
92      bitString = bin(num)[2:][::-1]
93      if(isMSB == 1):
94        x = 15
95      else:
96        x = 31
97      for i in bitString:
98        if int(i) == 1:
99          if(freqReg == 0):
100           self.freqReg0[x] = True
101         else:
102           self.freqReg1[x] = True
103       else:
104         if(freqReg == 0):
105           self.freqReg0[x] = False
106         else:
107           self.freqReg1[x] = False
108       x= x - 1
109     return 1
110
111
112   def setFreq0MSB(self,num):
113     return self.setFreqRegister(0,1,num)
114
115   def setFreq0LSB(self,num):
116     return self.setFreqRegister(0,0,num)
117
118   def setFreq1MSB(self,num):
119     return self.setFreqRegister(1,1,num)
120
121   def setFreq1LSB(self,num):
```

```
122       return self.setFreqRegister(1,0,num)
123
124     def setEntireFreqReg0(self,num):
125       actualValue = self.calculateFrequency(num)
126       if(actualValue > 0x3FFFFFFF):
127         return -1
128       self.setFreq0LSB(actualValue & 0x3FFF)
129       self.setFreq0MSB(actualValue >> 14)
130       return 1
131
132     def setEntireFreqReg1(self,num):
133       actualValue = self.calculateFrequency(num)
134       if(actualValue > 0x3FFFFFFF):
135         return -1
136       self.setFreq1LSB(actualValue & 0x3FFF)
137       self.setFreq1MSB(actualValue >> 14)
138       return 1
139
140
141     def getFreqReg0(self):
142       return (self.boolListToInteger(self.freqReg0))
143     def getFreqReg1(self):
144       return (self.boolListToInteger(self.freqReg1))
145
146     def sendFreqReg0MSB(self):
147       sendFreqRegNum = self.boolListToInteger(self.freqReg0)
148       self.spi.xfer([sendFreqRegNum >> 24, (sendFreqRegNum >> 16) & 0xFF])
149
150     def sendFreqReg0LSB(self):
151       sendFreqRegNum = self.boolListToInteger(self.freqReg0)
152       self.spi.xfer([(sendFreqRegNum >> 8) & 0xFF, (sendFreqRegNum) & 0xFF])
153
154     def sendFreqReg1MSB(self):
155       sendFreqRegNum = self.boolListToInteger(self.freqReg1)
156       self.spi.xfer([sendFreqRegNum >> 24, (sendFreqRegNum >> 16) & 0xFF])
157
158     def sendFreqReg1LSB(self):
159       sendFreqRegNum = self.boolListToInteger(self.freqReg1)
160       self.spi.xfer([(sendFreqRegNum >> 8) & 0xFF, (sendFreqRegNum) & 0xFF])
161
162     def setFrequency(self, freq):
163       if(freq < 10000):
164         return -1
165       self.enableB28()
166       self.chooseFreq1()
167       self.sendControlReg()
168       self.setEntireFreqReg0(freq)
169       self.sendFreqReg0MSB()
170       self.sendFreqReg0LSB()
171       self.chooseFreq0()
172       self.sendControlReg()
173       return 1
174
175     def setFrequency1(self, freq):
```

```
176       self.disableB28()
177       self.enableHLB()
178       self.chooseFreq1()
179       self.sendControlReg()
180
181       calculatedValue = self.calculateFrequency(freq)
182       if(calculatedValue > 0x3FFF):
183         return -1
184
185       MSB = (calculatedValue >> 14) & 0x3FFF
186       self.setFreqRegister(0, 1, MSB)
187       self.sendFreqReg0MSB()
188       self.disableHLB()
189       self.sendControlReg()
190       LSB = calculatedValue & 0x3FFF
191       self.setFreqRegister(0,0,LSB)
192       self.sendFreqReg0LSB()
193
194       self.chooseFreq0()
195       self.sendControlReg()
196
197     def calculateFrequency(self, num):
198       #print "Calculated Value: " + str(int(num/(.0596)))*self.fudgeFactor
199       return int(num/(.0596))*self.fudgeFactor
200
201     def close(self):
202       self.spi.close()
203
204     #Converts a boolean array to a number
205     def boolListToInteger(self,lst):
206       return int( ''.join(['1' if x else '0' for x in lst]),2)
207
208 # Test function
209 def main():
210     print 'running in test mode'
211     m = minigen()
212     m.setFrequency(float(sys.argv[1]))
213     print "Frequency Register: " + bin(m.getFreqReg0())
214     m.close()
215
216
217 if(__name__ == "__main__"):
218     main()
```

Listing 5: PGA Control Script

```
1  #! /usr/bin/python2.7
2
3  import RPi.GPIO as GPIO
4  import time
5  import os
6  import sys
7
8  class pga:
9
```

```
10  def __init__(self, pin_0, pin_1, pin_2):
11    #Switch user
12    #sudoPassword = 'root'
13    #command = 'sudo -i'
14    #p = os.system('echo %s|sudo -S %s' % (sudoPassword, command))
15
16    #Default Gx pins
17    self.pinGx = [pin_0, pin_1, pin_2]
18    #self.pinGx = [4, 17, 27]
19
20    #6910-3
21    self.gainList = [0, -1, -2, -3, -4, -5, -6, -7]
22
23    #6910-2
24    #self.gaintList = [0, -1, -2, -4, -8, -16, -32, -64]
25
26    #6910-3
27    #self.gainList = [0, -1, -2, -5, -10, -20, -50, -100]
28
29
30    GPIO.setmode(GPIO.BCM)
31    GPIO.setwarnings(False)
32    self.updatePins()
33
34
35  def updatePins(self):
36    GPIO.cleanup()
37    for pos in range(0,3):
38      GPIO.setup(self.pinGx[pos], GPIO.OUT)
39
40  def setPinG0(self, pin):
41    self.pinGx[0] = pin
42    self.updatePins()
43
44  def setPinG1(self, pin):
45    self.pinGx[1]= pin
46    self.updatePins()
47
48  def setPinG2(self, pin):
49    self.pinGx[2] = pin
50    self.updatePins()
51
52  def setGainList(self, list):
53    if(len(list) == 8):
54      self.gainList = list
55      return True
56    return False
57
58  def getGainList(self):
59    return self.gainList
60
61  def printGainList(self):
62    print self.gainList
63
```

```
64    # Only Allows for gains set in the given list
65    def setGain(self, gain):
66      try:
67        binNum = '{:03b}'.format(self.gainList.index(gain))
68        #print binNum
69        binNum = binNum[::-1]
70        for pos in range(0, 3):
71          if int(binNum[pos]) == 1:
72            GPIO.output(self.pinGx[pos], 1)
73          else:
74            GPIO.output(self.pinGx[pos], 0)
75      except ValueError:
76        print "Gain not Found"
77
78
79  def main():
80    print "Running PGA test"
81    p = pga(4, 17, 27)
82    p.setGain(int(sys.argv[1]))
83
84
85   #self.gainList = [0, -1, -2, -5, -10, -20, -50, -100]
86  if(__name__ == "__main__"):
87    main()
```

Listing 6: Reset Script

```
1   #! /usr/bin/python2.7
2
3   # TODO the purpose of this script is to reset the minigen to a default state
4
5
6   # This script is designed to count as a test
7   print "Content-type:text/html\r\n\r\n"
8   print "<html>"
9   print "<head>"
10  print "<title>Reset-Procedure</title>"
11  print "<head>"
12  print "<body>"
13  print "</body>"
14  print "</html>"
15
16  # reprint index.html
17  with open('/home/pi/senior_design/www/index.html', 'r') as file:
18    line = file.readline()
19
20    while line:
21      #print "\""+line+"\""
22      print line
23      line = file.readline()
```