Development of a Vacuum Chamber Control System

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Contents

Abstract

The purpose of this research project was to develop a user-friendly interface and highly sensitive control system for a vacuum chamber. This control system monitors the pressure of the vacuum chamber in real time and displays this pressure to the user. After allowing the user to select a desired air pressure, the control system automatically evacuates air until that pressure is met and actively maintains that pressure within the chamber. This control system is built using a Raspberry Pi computer and an attached touchscreen. This device is connected to two vacuum pumps, a pressure sensor, and other components that are housed on a printed circuit board beneath the Raspberry Pi. The programming of the components and the graphical user interface (GUI) are completed on the Raspberry Pi in Python and PAGE, a Python GUI generator, and will allow the user to control the system with the hand-held touchscreen device.

The vacuum chamber control system is intended to be used as a tool for experimentation by simulating the low-pressure environment present at high elevations. One project that will eventually be tested inside of the vacuum chamber is a new acoustic temperature measurement system.

1 INTRODUCTION

Vacuum chambers are enclosed systems from which gases are extracted by a vacuum pump, creating a low-pressure environment for experimentation. The vacuum pump control system developed in this project will be used to test the efficacy of an acoustic temperature measurement system at various altitudes. One method of using sound to measure temperature is determining the time it takes sound waves to travel a certain distance, and relating that speed with air temperature. This technology would be best employed at high altitudes of up to 100,000 feet where conventional temperature measurement systems are largely influenced by solar flux rather than solely the surrounding gas temperature. The acoustic temperature measurement system is intended to measure the temperature at various elevations within high-altitude balloons supplied by Raven Industries. The vacuum chamber control system will simulate the low-pressure environment to test the accuracy of the temperature and pressure measurements at high altitudes.

The goal of this research project was to develop a vacuum chamber control system that allows the user to easily monitor and control the pressure inside of the vacuum chamber. The control system is able to maintain a constant pressure by automatically turning the vacuum pumps on and off in order to reach and maintain a desired air pressure. The user interface allows the user to select the desired air pressure, which in turn controls the vacuum pumps until the desired air pressure is met.

2 BROADER IMPACT

The vacuum pump control system will aid in reducing the costs of testing the acoustic temperature measurement system by creating a low-pressure environment that exists in the upper atmosphere. If the results from testing the acoustic temperature measurement system prove that this new method is a more accurate way to collect temperature data at high altitudes, Raven Industries will benefit from better understanding the high-altitude environment that their balloons are designed for. The impact from this knowledge could include better designed balloons, leading to longer flight times, higher altitudes, and heavier payloads.

3 PROCEDURE

3.1 Materials

The first step to designing a control system is the selection of components to allow for an efficient and compact product. The main component is a Raspberry Pi computer that is the size of a deck of cards. In addition to its small size, the advantages of using the Raspberry Pi 3 include the easily-maneuverable user interface, sizable RAM, and USB and HDMI ports. Attached to the Raspberry Pi is an Adafruit 2.8-inch capacitive touch screen display. Present inside of the vacuum chamber is a Sparkfun Precision Altimeter and a Dwyer Pressure Transmitter. Both of these devices are capable of measuring the air pressure inside the chamber. Attached to the vacuum chamber are two vacuum pumps.

In order to create a compact and portable device, the rest of the components are housed on a printed circuit board the same size as the Raspberry Pi, mounted directly underneath the touchscreen and Raspberry Pi. Long screws run through the Raspberry Pi and touchscreen case, through the corners of the circuit board, and into the base platform. Present on the circuit board are four sets of wire screw terminals, two DC barrel jacks, two motor drivers, current monitor, analog to digital converter (ADC), two pull-up resistors, and a 40-pin header connecting to the Raspberry Pi pins.

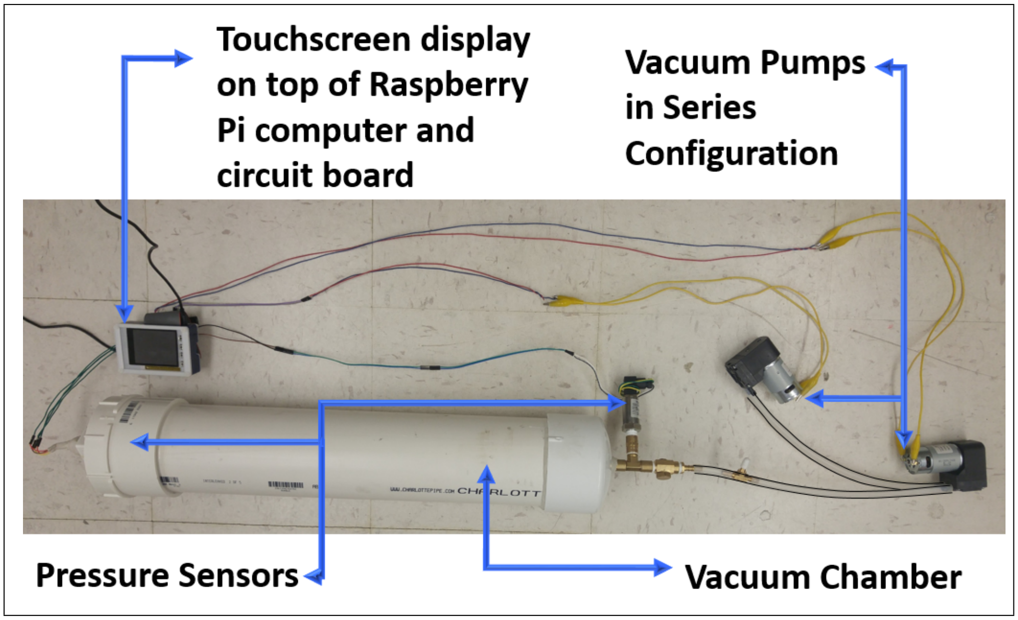

Figure 2: **Control System Layout. (Authors'work.)** All major components are shown.

The purpose of the motor drivers is to allow the Raspberry Pi to control the vacuum pumps and the speed at which they operate. Each motor driver can control up to two vacuum pumps. Two motor drivers were used to allow for the possibility using four vacuum pumps in the control system to reach lower air pressures within the vacuum chamber. The motor drivers require a power supply of 2.5V-13.5V, and the vacuum pumps operate at 12V and 1A. Therefore, the selected external power sources connected to the DC barrel jacks supply up to 5A at 12V each. The motor drivers require three general purpose input/output connections to the Raspberry Pi to control the direction of motors as well as their on/off switches[7]. They also require a pulse width modulation (PWM) signal from the Raspberry Pi to control the duty cycle of the vacuum pumps [3]. This makes it possible to run the pumps at less than 100% to maintain a constant pressure by closely matching the leakage rate of the chamber. However, it proved to not be practical to operate a vacuum pump at a speed less than 100% at lower air pressures.

The Sparkfun Precision Altimeter can measure air pressure and temperature. For the purpose of the vacuum chamber control system, air pressure is the only data being read by the Raspberry Pi. This sensor is supplied by 3.3V DC from the Raspberry Pi. It communicates with the Raspberry Pi over the I2C interface [1]. The I2C lines use 10kΩ pull-up resistors connected between the I2C lines and the 3.3V power supply to keep the input pins in a high state when not in use and prevent shorts[4]. To confirm the Sparkfun Precision Altimeter pressure readings, another air pressure sensor was used in the control system.

The Dwyer Pressure Transmitter uses the standard 4-20mA current loop to transmit the air pressure. A 4mA supply current corresponds to 0 psia or 0 torr, while a 20mA supply current corresponds to 15 psia or 775.7 torr. To monitor the current, the supply current passes through a Sparkfun current monitor. This current monitor outputs an analog signal that corresponds to the current supplied to the Dwyer pressure sensor[5]. Using a 16-bit ADC, this analog signal is converted to a digital signal and transmitted over I2C to the Raspberry Pi[6]. This pressure sensor, unlike the Sparkfun sensor, is easily attached to the vacuum chamber by a quarter inch valve.

3.2 Circuit Board Design

The system was originally built and tested using a breadboard, but designing a circuit board was an essential step to the development of a compact system. The only physical design requirement for the circuit board was for it to be the same size as the Raspberry Pi housing with matching holes in the corners to allow for long mounting screws to go straight through the Raspberry Pi housing and circuit board. A two-layer board was utilized, with the design process occurring in Altium Designer. To make hand-soldering the board a possibility, all routes begin and end on the bottom layer of the board. This was necessary because no surface-mount components were used, and the industrial through-hole plating process was not available. Therefore, to make all electrical connections possible, a minimal amount of vias were used when connections could not possibly be made entirely on the bottom layer.

Instead of directly mounting the major electrical components (motor drivers, ADC, and current monitor) into the through holes, female headers were soldered on the PCB to allow for easy replacement of a part if it were to fail. The DC power supply inputs are on the left side of the PCB, while all other wires connecting to the pressure sensors and vacuum pumps are connected via screw terminals on the back side of the PCB.

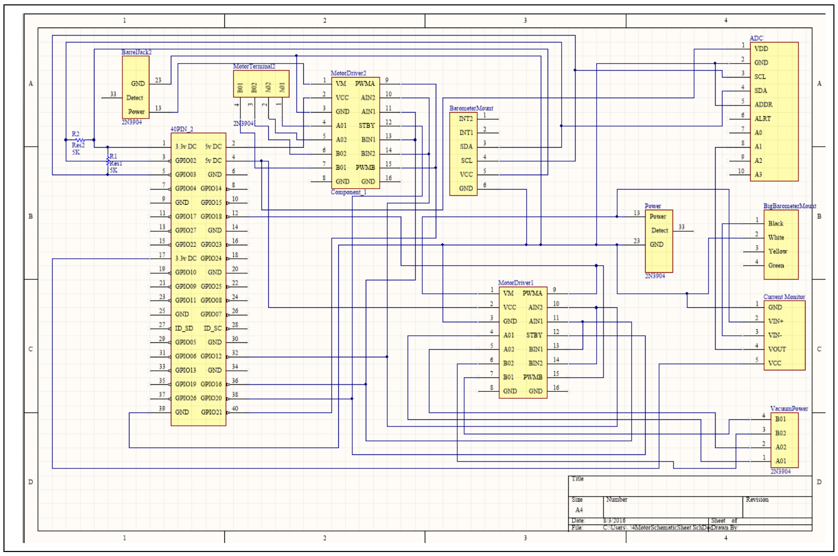

Figure 3: **Circuit Board Schematic (Authors'work.)** Circuit board schematic design occurred in Altium Designer.

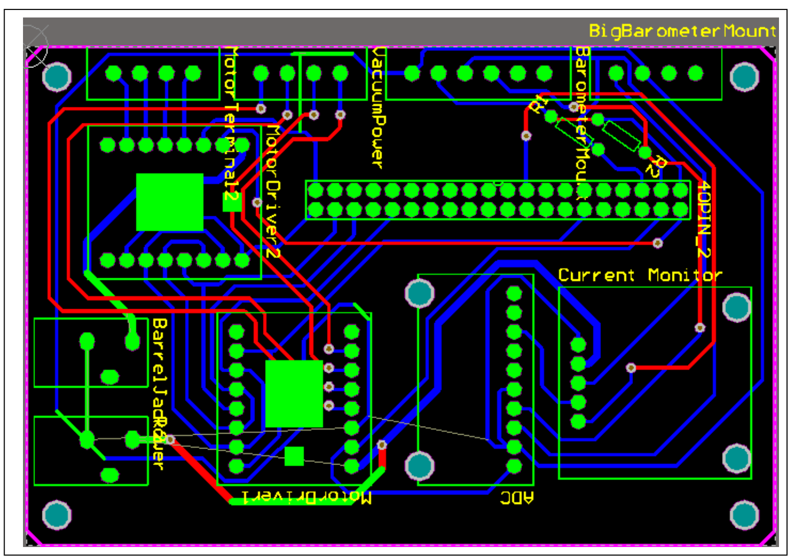

Figure 4: **Circuit Board Layout (Authors'work.)** The green layer is the component outlines and their pin holes. The blue layer is the bottom layer. The red layer is the top layer.

3.3 Graphic User Interface (GUI)

The graphical user interface was built through PAGE, a GUI developer specific for Python which is the supported programming language of the Raspberry Pi. The GUI was built with a two-tab configuration. The first tab includes a text box that displays the pressure in torr in the vacuum chamber, updating every second, and another text box that displays the desired pressure as well as start and stop buttons. The second tab is a keypad for inputting the desired pressure. To program the GUI so that the the pressure could update without pausing the main interface, threading techniques were used. These techniques were also used when programming the motor drivers to control the vacuum pumps, so that they could run simultaneously with the pressure sensor and the GUI itself [2].

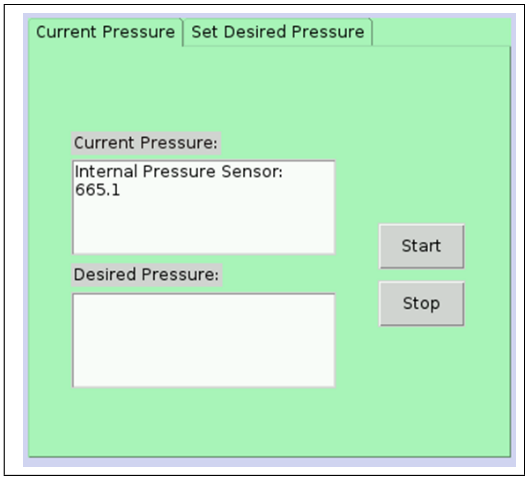

Figure 5: **Touchscreen Display, Tab 1. (Authors'Work).** Current pressure and desired pressure are displayed, along with a start and stop button.

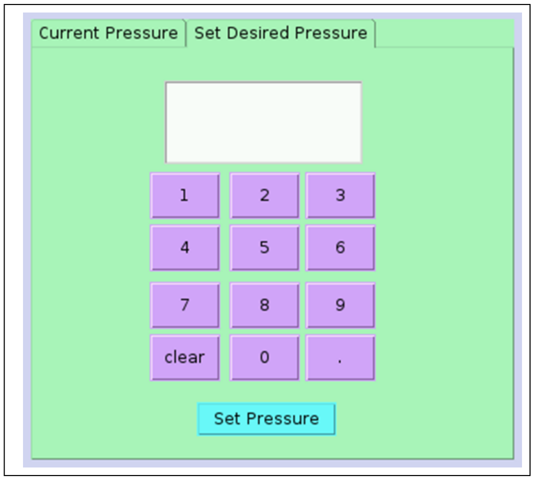

Figure 6: **Touchscreen Display, Tab 2. (Authors'Work).** The user can set the desired air pressure using the keypad.

4 RESULTS

4.1 Accuracy

Throughout the entirety of this project, three different pressure sensors were used to monitor the air pressure within the vacuum chamber. The first of these sensors was a mechanical gauge with a display reading to the nearest psi or about 57 torr. Given that this mechanical gauge had such low resolution and could have been calibrated incorrectly, its readings were treated with skepticism. However, it was still helpful to have a mechanical method of reading air pressure while the control system was being built. The first pressure sensor interfaced with the Raspberry Pi was the Sparkfun pressure sensor. This pressure sensor was able to supply consistent and accurate pressure readings that were comparable to the mechanical gauge. Given that the Sparkfun pressure sensor has over 100 times the resolution of the mechanical gauge and is likely less prone to manufacturing error, it was not surprising to see a slight discrepancy in air pressure between the two pressure sensors.

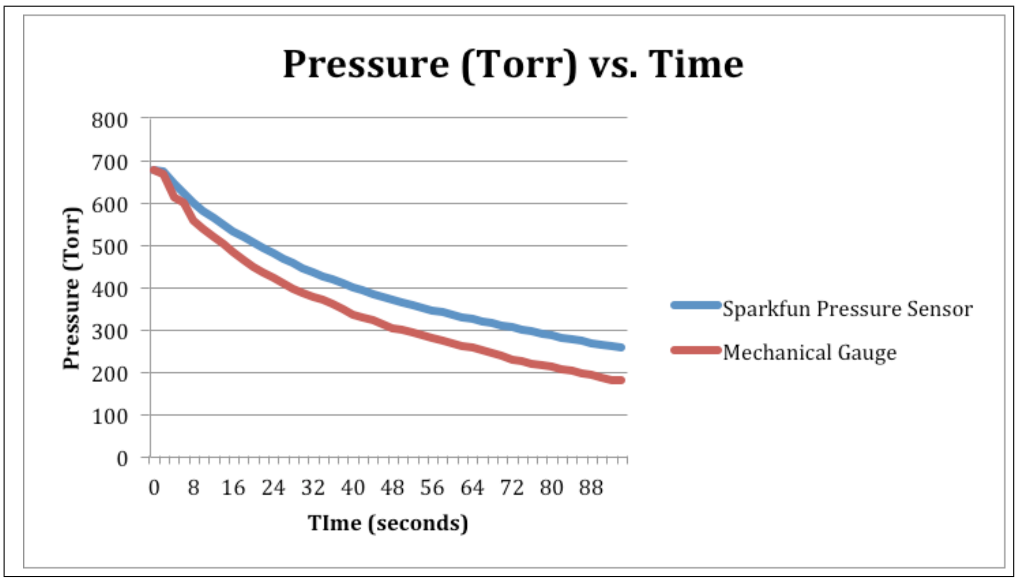

Figure 7: **Accuracy of different pressure gauges. (Authors'work.)** Pressure vs time readings are compared between the Sparkfun Pressure Sensor and mechanical pressure gauge.

In an effort to confirm the accuracy of these two pressure sensors, a Dwyer pressure sensor was added and interfaced with the Raspberry Pi. This pressure sensor, which requires the current sensor and ADC to read the supply current, was able to produce stable pressure readings when the vacuum pumps were turned off. However, when the vacuum pumps were running this pressure fluctuated about 30 torr above and below the actual air pressure within the chamber. In the moments when the vacuum pumps started and stopped instantaneously, the Dwyer pressure sensor fluctuated up to 100 torr above or below the actual air pressure. By testing this pressure sensor while hooked up to its own power supply, we were able to conclude that most of the fluctuation is due to the physical placement of this pressure sensor and not electrical reasons.

Since the Dwyer pressure sensor was set up in-line with the air evacuation tube, air turbulence was the main cause of the fluctuating readings especially when the pumps would start and stop. Additional sources of error could include false readings from the current sensor and ADC during supply current spikes and dips when the vacuum pumps stall. However, at this point it was clear that the Sparkfun pressure sensor was the most practical pressure sensor to use with its more stable readings and $90 lower hardware cost. To allow for optional future testing, the circuit board was still configured to allow for the Raspberry Pi to read the pressure with the Dwyer pressure sensor.

4.2 Efficiency

Currently, a two vacuum pump system is being used. These two vacuum pumps have been tested in two different configurations to determine the most efficient arrangement. The first configuration was a parallel configuration, where both pumps independently evacuated air from the chamber. This was possible by using a T-joint in the tube that is attached to the chamber. This parallel configuration allowed the system to have nearly double the air evacuation rate compared to a single vacuum pump, but it reached the same minimum pressure as a single vacuum pump of only 196 torr or 0.26 atmospheres. Since a much lower air pressure was desired, a series configuration was also tested.

In a series configuration, one vacuum pump sucks air from the output of the other vacuum pump, which sucks air from the chamber. Therefore, air is evacuated out of the chamber, through a vacuum pump, and finally through the other vacuum pump. This arrangement allows the air to move from a low pressure environment, to an intermediate pressure environment, to the air pressure of the external environment. By creating lower pressure differentials between the input and output of the vacuum pumps, less strain is put on the motors allowing them to reach lower air pressures in the chamber. Even though this configuration evacuates air at a slower rate to begin with, it is able to reach a much lower pressure of 76 torr, less than half the pressure of a single vacuum pump or two vacuum pumps in a parallel configuration. It has yet to be determined if a third vacuum pump added in the series configuration will enable the system to reach a lower air pressure than two vacuum pumps in series.

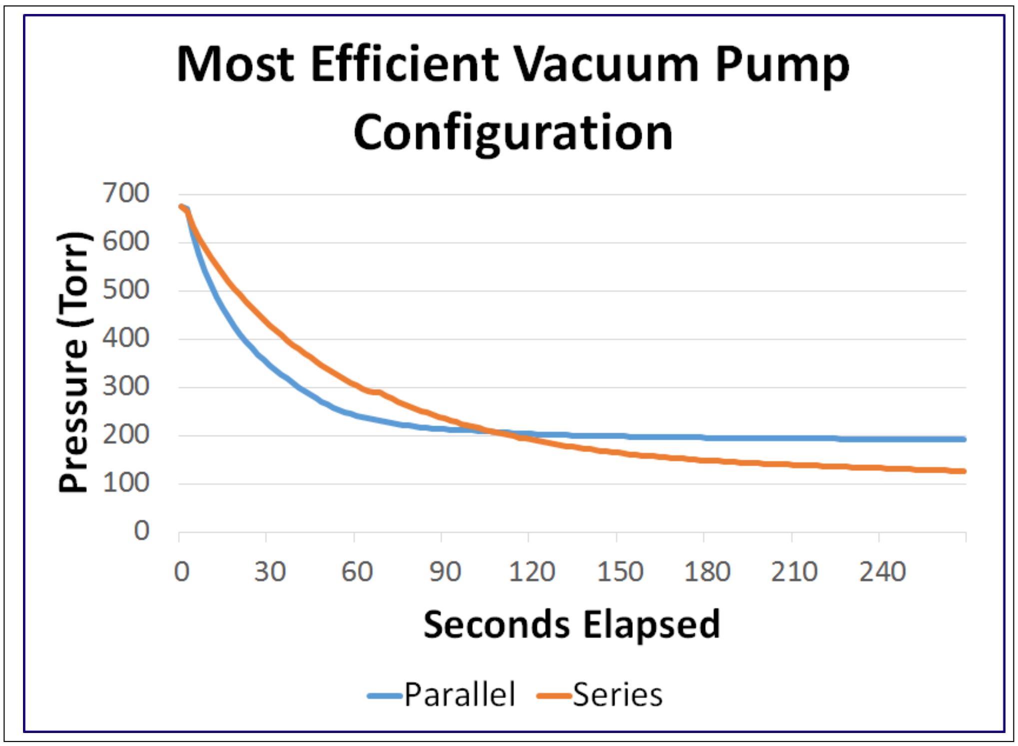

Figure 8: **Most Efficient Vacuum Pump Configuration. (Authors'work.)** Parallel and series configurations of two vacuum pumps are compared. The series configuration, shown in orange, was able to reach a lower pressure than the parallel configuration.

4.3 Autonomy

After the user selects a desired pressure and presses start, the control system automatically evacuates air until that pressure is reached and maintains that pressure. The code for this application does this by comparing the desired pressure with the live readings of the actual pressure from the Sparkfun pressure sensor. Initially, the code was set up to slow the speed of the vacuum pumps once the actual pressure came within ten torr of the desired pressure. It was then discovered that rapidly turning the pumps on and off with a PWM signal allowed air to leak through the vacuum pumps into the chamber, especially while operating at lower air pressures. Since this vacuum chamber is intended to be used at pressures below 100 torr, the vacuum pumps now only operate at full speed until the desired pressure is met.

The vacuum pumps automatically shut off once the actual pressure is less than the desired pressure, and turn back on once the actual pressure is greater than the desired pressure. This method is capable of maintaining an air pressure within 0.2% of the user-selected pressure.

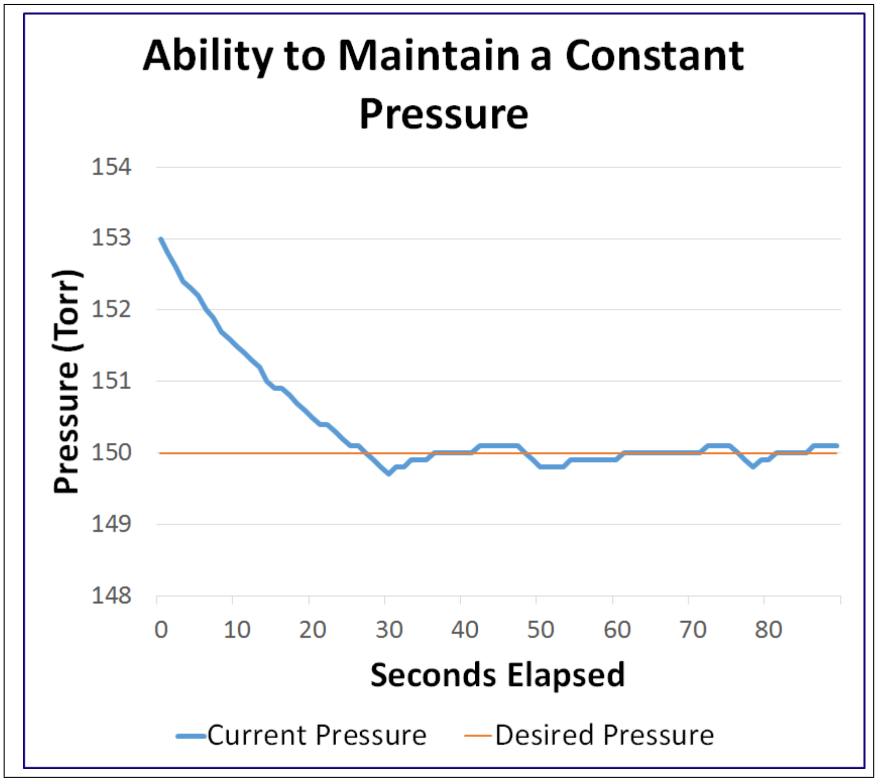

Figure 9: **Ability to Maintain a Constant Pressure. (Authors'work.)** By turning the vacuum pumps on and off, the current air pressure (blue line) was able to stay within 0.2% of the desired pressure (orange line).

5 DISCUSSION

Though one of the original goals of the project was to create a fully-functional GUI that can be displayed and controlled solely on the touch-screen, the GUI is currently only functional with an external mouse and monitor attached to the Raspberry Pi. Problems in the code need to be addressed to allow for easily switching between the monitor and the touchscreen. Eventually, one of the physical buttons next to the touchscreen could be programmed to make this switch with a single press.

Many oil-free vacuum pumps can cost hundreds of dollars. To save money, two $15 vacuum pumps were used in this control system. The efficiency of these pumps has been maximized with the series configuration, but the lowest desired pressure of 12 torr has not been met. With the limitation of using these $15 vacuum pumps, this control system has succeeded in achieving the lowest pressure possible with the materials in use and being able to maintain that pressure. Further testing will yield if a lower air pressure can be reached with the addition of at least one more vacuum pump added in the series configuration.

Once more vacuum pumps are added, it would be in the interest of portability to create a housing for all of the vacuum pumps. A 3d-printed case to hold the vacuum pumps would keep the system more compact while allowing more wires to be stranded together. This aesthetic and practical addition should be completed as soon as the number of desired vacuum pumps is determined.

6 CONCLUSION

This project succeeded in creating a control system to monitor and control the air pressure within a vacuum chamber. The components necessary for this system are housed on a circuit board beneath the touchscreen and Raspberry Pi. A user-friendly GUI was developed to allow the user to select a desired air pressure. The system automatically controls the vacuum pumps to reach the desired pressure and then maintains that pressure. The control system is able to monitor the pressure within the chamber with two different pressure sensors, but the Sparkfun sensor proved to be the best sensor for the purpose of this project. The most efficient vacuum pump configuration is placing the pumps in series. More vacuum pumps will be added in series to reach a lower air pressure, and the circuit board has been designed for the easy addition of two more vacuum pumps. This should allow the system to reach a lower air pressure than the current minimum capability of 76 torr. Most importantly, this control system can maintain an air pressure within +/- 0.2% of the desired pressure, creating a stable environment for testing the acoustic temperature measurement system.

7 ACKNOWLEDGEMENTS

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