PlastiSense

Aaron Achildiyev EE, Aidan Belanger EE, Victor Lam CSE, and Adrian Mora CSE

Abstract— **Plastic, first synthesized in the early 1900's, has many useful properties such as being waterproof and malleable and is cheap to manufacture. These qualities led to a plastics surge during WWII which continues today. Roughly 8.3 billion metric tons of plastic have been produced in the last six decades, and we are starting to see it in our oceans, our landfills, and even our rain [1]. Microplastics, plastic fragments that are less than 5 millimeters in length, have been found in many sources of water, and more recently, in our bloodstreams. Current systems used to detect these microplastics cost tens of thousands of dollars and are relatively large. To make microplastics sensing cheaper and more portable, we designed a Raman spectrometer, an optics-based sensing system that will detect the presence of polystyrene, the most abundant microplastic. Our design uses a 3D printed chamber to eliminate light pollution and ensure optical elements are perfectly fitted and aligned. The system is lightweight, portable, and significantly cheaper than any other optics-based system.**

I. INTRODUCTION

Plastics, we're surrounded by them. We drink water from plastic water bottles, we hold our groceries in plastic bags, and we sell packaged products like potato chips in plastic. However, plastics are not a naturally occurring material and are not biodegradable. Most plastics can be recycled, however a lot of them end up in our natural water ecosystems. To increase awareness to the extent of microplastic pollution we decided to build a Raman spectrometer which will sense the presence of microplastics in water. Existing Raman spectrometers are meant to survey various substances with many lasers and come with special targeting software. This system is intended to only sense a particular type of plastic, polystyrene, and this specificity is what has allowed us to cut costs dramatically. PlastiSense is affordable so that the average person can purchase a device and test their own water for microplastics.

A. Significance

In 2019, scientists working with the United States Geological Survey discovered microplastics in Colorado rainwater [2]. This means that microplastic particles are being evaporated into the clouds, and then precipitated with the rain. The consequence of this is unpredictable microplastic pollution in places that one normally would not expect them. Animals and humans alike consume microplastic contaminated food and water unknowingly. The University of Newcastle in Australia published a report estimating that the average person consumes five grams of microplastics a week, the equivalent weight of a credit card. The long-term consequences of microplastic consumption are not yet well understood, but it is known that plastics can combine with other harmful chemicals known to cause fertility issues, cell mutations and cancer [3]. Most recently, scientists have found microplastics in blood for the first time. In a Dutch scientific report published in 2022, nearly 80% of the twenty-two anonymous healthy volunteers have been found to carry microplastics in their blood samples [4]. More than a third of the samples contained polystyrene, the microplastic that PlastiSense was designed to sense.

B. Context and Competing Solutions in the Marketplace

There are several methods that have been used to detect microplastics in water, such as spectroscopy, filtering, sieving, and elutriation [5]. One filtering technique uses manta nets, which simply involves dragging a manta net through the water, or for smaller samples, pouring water through it. Its limitation is that the net cannot distinguish between different types of microplastics or identify by itself if there are microplastics. For spectroscopy-based solutions, there is Fourier transform infrared (FTIR) and Raman spectroscopy. The primary limitation for FTIR systems is cost as infrared lasers are extremely expensive. For Raman spectroscopy solutions, Thorlabs offers a modular Raman Spectrometer for $13,325.00 [6] and Ocean Insight offers a Raman Spectrometer for $14,649.62 [7]. Our solution may not be as sensitive or as versatile as these competing products, but it is more affordable and can be quickly deployed for microplastic measurement readings in water.

Competing Solutions (Non-Raman)	**Advantages**	**Disadvantages**
Manta Net [8] 	• Sample large volumes of water	• Requires boat • Time Consuming

FTIR Spectrometer [9] 	• Extensive spectral libraries to survey an abundance of microplastics	• Expensive ($13,500) • Can only detect particles of a certain thickness • Requires Sonification of sample
Competing Solutions (Raman Spectrometers)		
Thor Labs Raman Spectrometer Kit 	• Can detect Raman wavenumber responses from 500 cm^{-1} to 1800 cm^{-1} • Great SNR (700:1) • Max Power: 250 mW	• Expensive ($13,325) • Modular kit that must be constructed. • Not portable; requires optical bench
Ocean Optics Miniature Raman Spectrometer 	• Portable; lightweight • Able to detect various Raman responses from 150 cm^{-1} to 3400 cm^{-1}	• Expensive ($14,649.62)

Table 1: Competing Solutions

C. *Societal Impacts*

PlastiSense is designed for science enthusiasts and the average person alike to test the quality of their water so that they become more aware of what they are consuming and realize that the plastic we throw away every day does not just disappear. Scientists can use PlastiSense to conduct research on local ecosystems and see how the environment is polluted. The average person can take a sample of their drinking water and put it in the sample chamber of PlastiSense. Then, with a quick push of a button, one can see if plastics are present within the water.

D. *System Requirements and Specifications*

The system lives in a small plastic encasing, measuring 4200 cm^3 in volume, approximately 3 kilograms in weight, and $800 in cost so that it is easily affordable. The system should be responsive enough so that the user can get a measurement reading displayed within five seconds of startup. Below is a table of PlastiSense quantitative, justifiable specifications.

Requirements	**Specification**	**Value**
Portable	Weight Volume	<3kg 30cm x 14 cm x 10 cm
Responsive	Latency	<5s reading
Sturdy	Alignment	Aligned through CAD models & justified through inspection
Affordable	Cost	$800

Table 2: Requirements and Specifications

II. Design

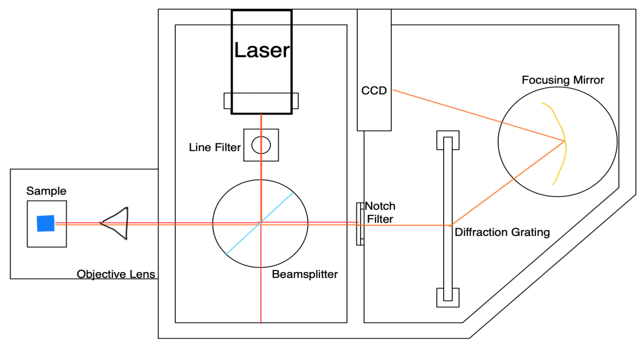

Figure 1: Aerial Diagram of PlastiSense

A. *Overview*

There are many ways to detect different molecules in water, but spectroscopy has been the most popular technique for detecting microplastics. We decided to implement a Raman Spectroscopy system because we had found a research paper claiming to have created a working microplastics sensor for 300 dollars [10].

In our system, we use a laser to excite microplastic molecules in a sample, and then measure the light that is emitted when the molecule goes back to ground state. We then use a charged couple device (CCD), which is a primitive camera, to detect the photons of the Raman signal coming from the sample.

We considered using a solution like the MantaNet, that would be a box with a manta-net that would catch microplastics in a net. The problem with this approach is that we would have an impossible task of identifying and distinguishing the different types of plastics captured. We also considered using an IR based spectroscopy system called FTIR but we were strongly advised against this approach due to the projected expense.

Using our CCD, we can read the intensity of light sensed by the pixels as voltage values. However, we need to graph these values, so we decided to use two separate devices, one for controlling and reading in the data from the CCD and another for graphing. To connect these two devices, we decided to use SPI with a RaspberryPi as the master and the STM32 as the slave. Using the RaspberryPi would allow us to set up the system on a network or remotely. In our case, we had issues connecting to the eduroam network, but connecting to a home network by WiFi or by ethernet are both supported options.

B. Why Did We Choose Raman Spectroscopy Over Other Technologies?

Raman spectroscopy has been a widely used technique for particle detection and it requires some basic components such as a laser, a notch filter, a diffraction grating, and a CCD. We chose these devices based on cost, quality, and availability. Our laser for example was lent to us by Prof. Arbabi and our CCD was one of the more affordable options we found. The laser has an integrated driver, so it saved us from having to design one ourselves. There was extensive documentation and firmware online documenting how to use our CCD [11]. This is also the reason we chose to use the STM32 and RaspberryPi, as the code to drive the CCD and communicate with the STM32 were developed for these boards. Below are a few graphical results of our spectroscopy sensing.

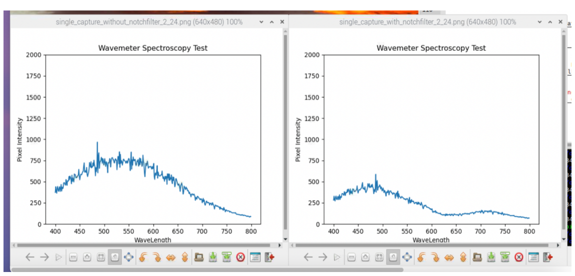

Figure 2: PlastiSense GUI representing intensity of light vs. wavelength when sensing white light from a flashlight emitting from a point source in our sample chamber. The left graph is without a notch filter, and the right graph is with a 633nm notch filter.

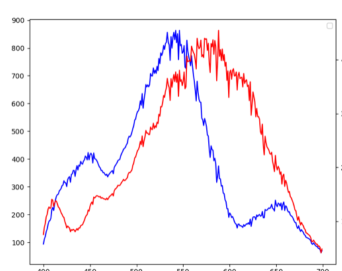

Figure 3: An updated graph plotting intensity vs. wavelength after improving the alignment of our system. In red is white light from a point source separated into its component wavelengths and dispersed across our CCD. In blue is the same light after being filtered with a 633nm notch filter.

Other options we explored were using the BeagleBone Black (BBB) since we all had experience with it and it met the hardware requirements for our system. However, using the programmable realtime unit on the BBB proved difficult; we could not run a simple blinky program on it.

C. Trade-offs

To keep our project affordable, we needed to use a lower quality notch filter which didn't block out enough of the laser light, subsequently masking our Raman response. Additionally, we chose to use a linear CCD which was designed for bar code scanning and was too slow to implement lock-in amplification. With a larger budget, a 2D array CCD might have made for better sensing. Our laser choices were also constrained as they are often expensive and using lasers with high power require special safety equipment and a laser safe lab.

D. Hardware Block Diagram

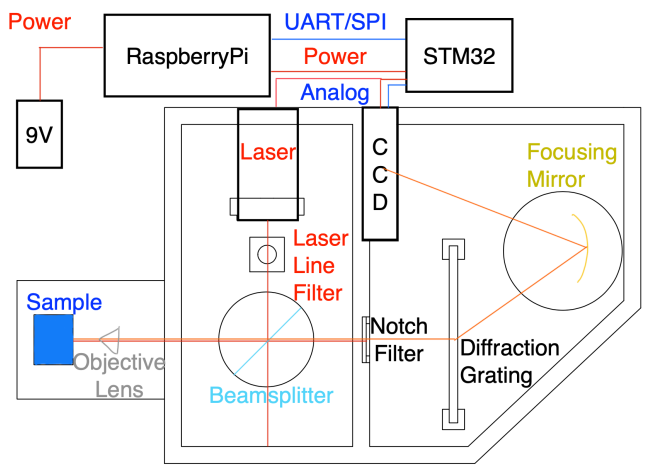

Figure 4: Hardware Block Diagram

In the Hardware Block Diagram above, we have a laser module which emits to a line filter, purifying the light, through to a beam splitter where some of the laser is redirected through a microscope objective lens. The objective lens focuses it, onto the sample being tested, while the rest continues on to hit a light dump.

The backscattered Raman response is then collected through the objective lens, where it is collimated, and passes through the beam splitter again. Note that the light is going backwards through the objective lens which is why we have a collimating effect. The light that makes it through the beam splitter then passes through a notch filter where most of the incident laser light is filtered out. The remaining light is then directed to the diffraction grating.

The diffraction grating splits the light at different angles depending on its wavelength. Having calculated the angle of diffraction, we place a focusing mirror to focus the light onto our CCD. Our CCD at the end of the integration period shifts out the data as analog voltages and the PCB converts the analog signal to digital in the STM32 before sending it over to the RaspberryPi where it is processed and plotted in a GUI which can be seen on VNC viewer.

E. Software & Firmware Block Diagram

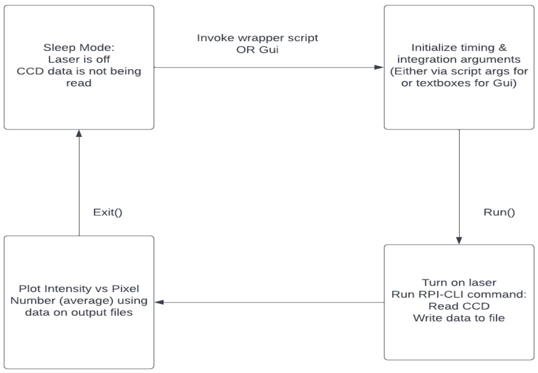

Figure 5: Software Block Diagram

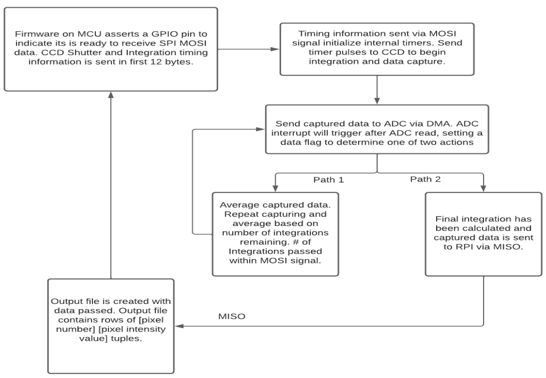

Figure 6: Firmware Block Diagram

The software diagram in Figure 5 depicts the primary states of the system, controlled by Raspberry Pi: sleep, initialization, sensing, and processing. The system is initially in the sleep state and wakes to allow the timing arguments to be specified by the user before it calls the firmware scripts. The firmware lives on the PCB which is responsible for the data collection. As can be seen in Figure 6, the diagram begins from the top right where the firmware gets the initialization values sent from the RaspberryPi, which then starts running the CCD for a set number of times specified in the call to the firmware. Other timing variables control the electric shutter and integration gate of the CCD. Once the firmware has finished running, it will send the data back to the RaspberryPi which will process the data (noise removal and shifting) and plot it on a graph.

III. THE REFINED PROTOTYPE

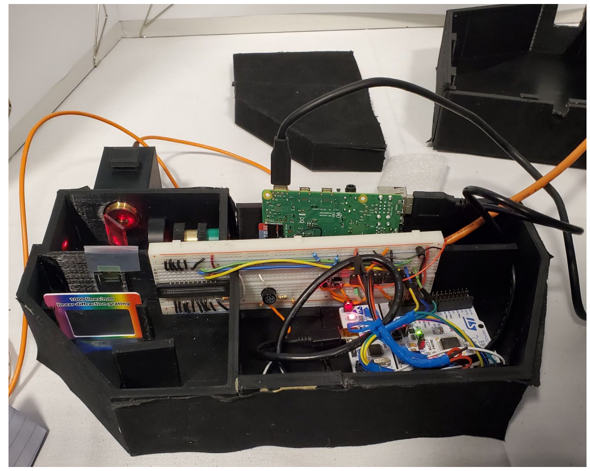

Figure 7: Real Aerial View of PlastiSense with a Breadboard (top is removed to show insides)

A. Prototype Overview

Our prototype design, as shown in Figure 7, is in a 3D printed chamber. This chamber is all black to limit the amount of light reflected and to absorb as much optical noise as possible. The chamber allows us to have our components fixed into place with sturdy mounts that are always aligned. The chamber is split up into two sections, the optical chamber (top half) and the spectroscope chamber (bottom half).

The optical chamber alone took 8 hours to print, so combining them would be too big for our 3D printer. It would also make it hard to test repeatedly for minor changes as well as contribute heavily to plastic waste for each prototype.

The PCB we designed lives in the spectroscope part of the chamber as it houses the CCD, and this would be running the firmware. The RaspberryPi would be connected to the PCB with a few cables for communication and power. In Figure 7, there is no PCB shown, because the breadboard is used as a substitute.

B. List of Hardware and Software

List of Hardware:

- VLM2.3-5L 5mW 635 nm laser module which chouses a laser drive and diode
- FL635-10 laser line filter
- 18x30 cm 70R/30T Plate Beamsplitter
- Two 10 x achromatic objective lenses
- 5mm quartz cuvette
- Everix 633 nm CWL TECHSPEC Ultra-Thin OD3 Notch Filter
- TCD-1304 Linear CCD
- STM32FR01RET6 MCU
- Raspberry Pi Gen 4
- 1000 lines/mm Linear Diffraction Grating
- 25 mm Dia. X 50mm FL Protected Gold Concave Mirror

Our firmware components to drive the CCD come from a third party source, Esben Rossel, who manages the TCD1304 wiki. Other major software we are relying on include VNC viewer for viewing the GUI live on the RaspberryPi.

C. *Custom Hardware*

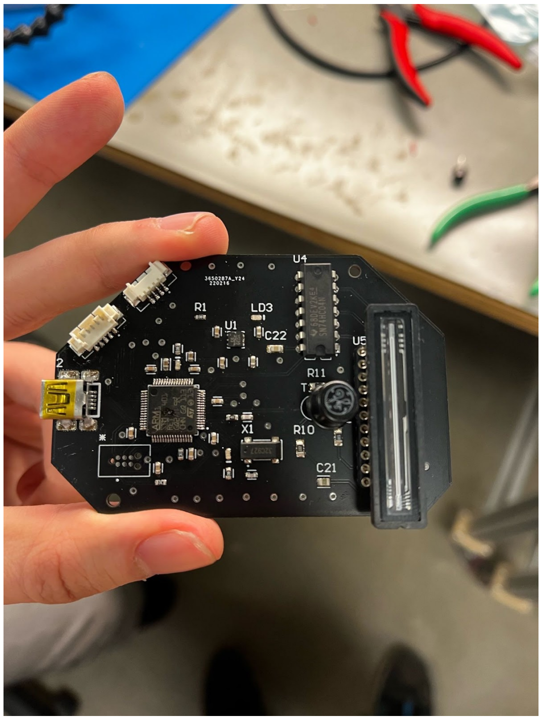

Figure 8: Populated PlastiSense PCB

Our PCB, shown in Figure 8, houses:

- STM32F401RET6 MCU with SPI, UART, and USB communication lines
- A TCD-1304 Linear CCD
- A SN74HC04 Inverter
- A LD39050PU33R Power Regulator which drops an input 5V to 3.3V for the MCU, inverter, and CCD
- A 2n404 germanium PNP BJT Transistor
- An ABS25-32.768kHz crystal oscillator
- Various capacitors and resistors

The MCU can be programmed through JTAG using an ST-Link device. Once running, the MCU sends master clock (fm), integration clear gate (ICG) and shutter gate (SH) signals to the inverter. The inverter adds a 90-nanosecond delay to the rise time of each of the signal lines as a requirement for the CCD. Using fm as a time reference, the CCD uses the SH signals to control the integration time and the ICG signals the moment the pixel values are sent to the shift register of the CCD. The CCD then outputs an analog signal which is amplified by a PNP transistor and received by the ADC of the MCU. Upon receiving the analog signal from the CCD, the MCU converts it to a digital value and relays that to the RaspberryPi.

We have currently populated and tested two PCBs of this design. We were able to program our MCU and verify our fm and SH signal lines. We had trouble with our ICG signal line which prevented us from integrating the PCB into our system.

D. *Prototype Functionality*

Our PlastiSense prototype does not function as we first envisioned it would, however there are certainly some goals we accomplished while making our design. Originally, we wanted to create a product that can be used to sense a particular molecule's Raman response. However, after many tests and some theoretical response calculations, we have confirmed that our system is not sensitive enough to distinguish the weak signal when compared to the noise that is being picked up on our CCD sensor. Therefore, it is not possible to certifiably identify microplastics in any given sample we choose to study. However, we were able to build a low cost, small and efficient wavemeter, which could allow the user to differentiate the different wavelengths of light. We confirmed this by using the GUI to plot the graphs of intensity with and without the notch filter, showing a dip around the 633nm range.

E. *Prototype Performance*

Our prototype of PlastiSense has met the requirements and specifications in Table 2. We have a portable system weighing in at <3 kg, a volume of 4200 cm^3, and a responsive system with a latency of ten second read time, and lastly, the cost of our system is a lot cheaper than that of our closest competitors. Including the cost of our research and development, the total cost of developing and building our spectroscope is $800.

IV. Conclusion

Our PlastiSense project is in a good state. Our team has put in countless hours of work into this project and when looking back at our senior year as ECE majors, this has been the defining moment of what it truly feels like to be an engineer. We would like to stress the fact that our project is by no means a completed project. There are still plenty of things our team could work on to improve PlastiSense, such as upgrading the CCD and the laser. When we did our theoretical calculations, we originally thought that our components would work to capture the Raman response of polystyrene. Unfortunately, through countless hours of testing, we were not able to distinguish the Raman response from the noise.

Acknowledgments

We would like to thank Professor Arbabi, who was incredibly generous to lend out his laser, line filter, and most importantly his time. We would also like to thank our advisor, Professor Goeckel who met with us weekly and supported us throughout the entire project timeline. His advice has been invaluable, and we would not have had the resources we do without him. To our evaluators, Professors Niffenegger and Liu, we thank you for helping us “think outside the box”, challenging us in ways to improve our design, and pushing us when we needed it most. Last but not least, we would like to thank Esben Rossel as we would not nearly have been able to get to work as fast as we did without him. Esben’s open-source of his work allowed us to hit the ground running, and he was also kind enough to help us with setting up our system.

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Appendix

A. *Design Alternatives*

The first design option for sensing microplastics that we considered was Fourier-transform infrared spectroscopy, but for this option the infrared lasers would have been too costly for our 500 dollar budget and required complex optical designs.

We then considered using triad spectroscopy, spectroscopy using leds. Through triad Spectroscopy, we image a sample after shining different colors of light and detect the contours of microplastics. Through machine learning, we would then fit the shapes and color response of the objects imaged to known properties of microplastics. There was a nice breakout board for traid spectroscopy, available on Digi-key but we couldn't find a database with images to train a ML model.

The criteria for selecting an appropriate microplastic detection system included cost estimates and feasibility. This criteria led us to attempt Raman spectroscopy. We chose Raman spectroscopy because, in theory, the optics design was relatively simple and cost affordable.

B. *Technical Standards*

PlastiSense makes use of a number of different standardized communication protocols. Originally, we used USB communication to send data to and from the CCD in our initial design presented at MDR. When adding a RaspberryPi to our design to make it a more "engineered" project, we included SPI communication functionality as our protocol of choice.

C. *Testing Methods*

We were very serious about the practical testing methods we can implement to our design to test our functionality of PlastiSense. Firstly, our group borrowed a professional brand spectrometer from Professor Arbabi. We used this spectrometer to test our alignment and measurements of the spectroscope. Secondly, our team also got the chance to meet with Zili Gao of the Raman Spectroscopy laboratory here at UMass, where we tested the plastics samples that we were attempting to measure in our own spectrometer.

Our system must meet specifications of weight, volume, latency, and cost. To test the total weight of our systems we will place it on a bathroom scale. To measure the volume of our design we will measure the length, width and height of our chambers. To measure the latency of our CCD measurement we will time the response of our GUI. Cost wise, we just need to add up the cost of all the individual components we used.

D. *Project Expenditures*

Category	**Cost**
"Prototyping" – Materials purchased that were not used in final design.	$86.13
Hardware – Mirrors, lenses, laser, etc…	$373.85
PCBs (1st and 2nd Drafts)	$125.50

PCB BOM	$216.24
Total	$801.72

Table 3: Project Expenditures

E. Project Management

Aaron Achildiyev was the lead on the PCB design and team coordinator. He additionally aided in the alignment of the prototype system and aided in the PCB assembly. Aaron took much responsibility for learning Altium and designing the PCB over winter break.

Aidan Belanger researched the theory of Raman spectroscopy, aided in the design of the PCB, conducted much of the alignment of the prototype system, printed many of the early drafts of the housing and was responsible for most of the PCB assembly. Aidan is an EE undergraduate with some related background in fields and waves and microwave PCB design. Aidan often provided the group direction in the design and took the lead in debugging the pcb.

Adrian Mora researched the hardware required and implemented the hardware. This included understanding the stm32f401re nucleo board, tcd1304 linear ccd, and the RaspberryPi.

Victor Lam developed the designs for our 3D printed chambers in AutoDesk Fusion 360 and aided in the team's understanding of Esben's code. He took the lead in understanding the limits of 3D printing and working to get around them.

The Plastisense team is a cohesive unit of friends. Whenever a roadblock was reached by one of the members of the team, everyone would pull together and contribute to understanding and surpassing the obstacle. Much difficulty was encountered when first attempting to drive the CCD with a BeagleBone Black, the team pulled together and all attempted to learn to use the programmable realtime unit in the BBB. Additionally, there was much difficulty programming the MCU on the custom PCB. The team came together and attempted to work around the programming difficulties. Adrian and Victor wrote blinky code to be tested while Aidan and Aaron attempted to lift the preprogrammed MCU off of the development board. This method proved unsuccessful as heating the MCU most likely corrupted its memory and no blinky code was seen once it was mounted.

F. Beyond the Classroom

Aaron: Senior design project was instrumental in learning how to time manage and keep a strong work ethic throughout the entirety of senior year. The course is structured in a way where teamwork and team communication trumps everything else. I am so fortunate to be part of such a hardworking, and welcoming team. Technically speaking, I have learned a lot about spectroscopy and PCB design. As an electrical engineer, PCB knowledge is an important skill to have under my belt, and I am happy to have learned it. I know that it will be useful for me in my professional career.

Aidan: Learning the scattering theory and optical design behind Raman spectroscopy was particularly useful as I will be using Raman spectroscopy to characterize 2D heterostructures for nanoelectronics in the NanoEnergy laboratory while I pursue a graduate education at the University of Utah.

Victor: I took on the responsibility of CADing and printing out the optical and spectroscope chamber. In the process, I learned to use AutoDesk Fusion 360 and learned a bit about the physics behind diffraction gratings and concave mirrors. I also took the lead in understanding the driver code for the CCD and explaining it to the rest of the team.

Adrian: I had to learn very basic optic information about lenses, mirrors, diffraction gratings. I had to learn about common embedded system projects involving optical sensors. I also learned about the different programing environments and the challenges faced when programming stand-alone MCU's via SWD or JTAG.

G. Retrospective

In retrospect we believe we spent too much time attempting to predict our expected Raman response through theoretical calculations. Our time may have been better spent developing and refining the spectroscope portion of our design. Additionally, the STM32 proved to be very difficult to get programmed once mounted on our PCB. A simpler microcontroller that offered similar timing and memory capabilities may have suited the PCB design better. Something else we should've done is work on our project in smaller pieces. We often tried to skip steps and jump right to the end instead of making sure every little component works.

H. Contact

Aaron Achildiyev, from Boston, MA (e-mail:aachildiyev@umass.edu)

Aidan Belanger, from Greenfield, MA (e-mail: ajbelanger@umass.edu).

Victor Lam, from Boston, MA (e-mail:vslam@umass.edu).

Adrian Mora, from Miami, FL (e-mail: amora@umass.edu).