Carbon Fiber Microelectrode Array

Final Report

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4/20/2020

Background

Neural recording provides a method of measuring internal neural signal transmission and has revolutionized the neuroscience field. Carbon fiber microelectrodes have been shown to be marginally advantageous for neural recordings because they do not initiate a robust immune response when implanted into brain tissue.[1] This project intended to create a device that allowed the Hengen Lab of Washington University in St. Louis to implant a high number of carbon fiber electrodes into the brains of experimental mice. While this project has been interrupted before completion, this paper will summarize the progress made so far and detail future directions for potential continuation of the project.

Need Statement and Project Scope

The Hengen Lab's single-neuron chronic recording capabilities are currently limited by the low biostability of their nichrome microelectrodes, and they seek the development of a more biostable carbon fiber neural recording array that will enable long term (over 1 year) *in vivo* neural recordings.

The Hengen Lab studies the active self-organization of neural networks and a neural network's stability despite changing surroundings. The Hengen lab currently utilizes nichrome microelectrode arrays to achieve long-term recording of individual neurons. These nichrome electrodes cause microtraumas in the surrounding tissue that lead to an encapsulation response that limits the recording time span to a few months. To achieve his desired long-term recording capabilities, Dr. Hengen requires a new neural recording array that utilizes biostable carbon fiber

[1] Salatino, Joseph W et al

microelectrodes (CFMEs). Dr. Hengen requires that this new carbon fiber microelectrode array (CFMEA) be compatible with the modular, stackable HS-640 e-cube head stage system he currently uses, so that up to 512 channels can be inserted into the same animal. Additionally, Dr. Hengen requires that the end-product be able to be manufactured by a single individual in a lab setting in 1 day (< 8 hours). Completion of this project will include both a fully functioning carbon fiber neural recording array with up to 512 fully functioning carbon fiber recording electrodes as well as any custom tools/jigs that may be necessary in the manufacturing or construction of the arrays.

Design Specifications

While Dr. Hengen would prefer to minimize costs, he has provided a generous budget of $10,000. This generous budget emphasizes the importance of carbon fiber microelectrodes to the future of the neural recording field, and Dr. Hengen's desire to pioneer a new method of fabricating a carbon fiber microelectrode array. The number of recording channels per singular PCB must remain at 64 functional channels so that its data gathering capabilities are maximal and comparable to their current circuit boards, which also use 64 channels per PCB. The only difference is that the current PCBs employ nichrome tetrodes instead of carbon fiber electrodes. The PCBs must be able to be stacked up to 8 times for a total of 512 electrodes in one specimen. This will maintain the high standard of data collection currently held in the Hengen lab. The time to manufacture each circuit board must be within a 1hr time frame. This time frame is practical for a technician to complete a headstage in a single day. The mass, length, width, and height of the PCB must be less than or equal to the current PCB so that it does not affect the activity of the specimen once implanted. The CFMEA must not produce an immune response and should record action potentials for at least a year to be considered a success. Table 1 summarizes all the design specifications discussed above.

Specification	Metric
Cost of Development	< $10,000
Number of Available Recording Channels	64 channels per PCB, 512 for 8 stacked PCBs
Channel Functionality	64/64 channels function properly per PCB
# of PCBs that can be stacked	8 PCBs with one headstage (512 channels total)
Headstage compatibility	Any redesigned PCB must remain compatible with the current stackable HS-640 e-cube headstage system
Time to manufacture 1 functional PCB (64 channels)	< 1 hr
Single PCB mass	< 5 grams
Single PCB length	< 10.4 mm
Single PCB width	< 10.9 mm
Single PCB thickness	< .68 mm
Electrode Biological Response	No glial scarring around carbon electrodes
Electrode Functional Time Course	CFMEA must be able to record properly for longer than 1 year

Table 1: Design Specifications for the Carbon Fiber Microelectrode Array.

Discussion

Design Specifications

Since completion of the project was not possible due to the COVID-19 outbreak, not all design specifications laid out in table 1 were met. Table 2 summarizes the design specifications we were able to meet and those we were unable to meet.

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Cost of Development	< $10,000
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Table 1: Design Specifications met (green) and not met (yellow) for the Carbon Fiber Microelectrode Array.

Most of the design specifications met were surrounding the design of the PCB that is the foundation of the microelectrode array. An optimized layout for the 64 channel PBC was designed with the help of a PCB design consultant Bryan Broussard.[2] The redesigned PCB, shown in figure 1, creates a 16x4 (64 total) layout for the vias as opposed to the 15x4 + 4 extra layout on the old board. Furthermore, the spacing between vias was increased 74% in the X-direction and 45% in the Y-direction, making space for our alignment grid (figure 1). Appendix B shows technical drawings of the redesigned PCBs.

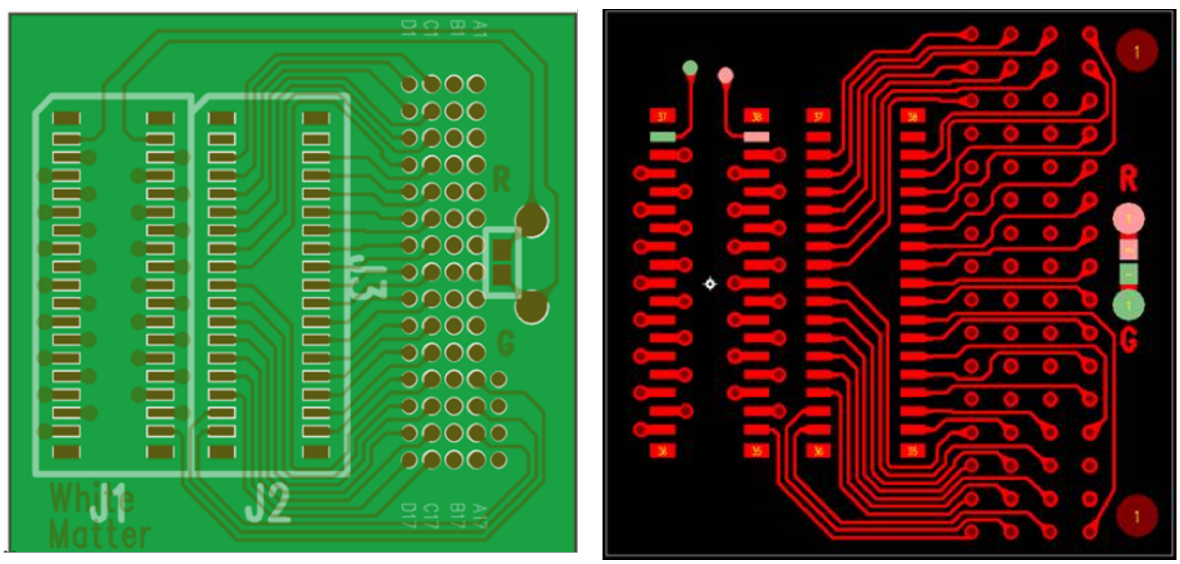


Figure 1: Side-by-side comparison of original PCB design (left) and PCB redesign (right). Red circles on the right upper and lower corners of the PCB redesign are unplated through holes to facilitate placement of the alignment grid.

The redesigned PCB maintains 64 possible recording channels. The dimensions of the final board were 10.4 mm long x 10.9 mm wide x 0.68 mm thick and weighed < 5 grams, meeting every size related design specification laid out for the PCB size in table 1. Furthermore, the redesigned PCB maintains compatibility with the current stackable HS-640 e-cube headstage

[2] Bryan Broussard, Dynamic FPC Design Inc., 2082 Vista Valle Verde, Dr. Fallbrook, Ca 92028

system, allowing up to 8 PCBs to be stacked on top of eachother for a total of 512 possible recording channels.

The final step of the project was to establish a system to solder carbon fiber microelectrodes to the 64 channels on the redesigned PCB. A 3D printed grid was designed that would overlay the 64 channels to create spaces to solder the electrodes to their respective pads on the PCB. Figure 2 shows a CAD rendering of the 3D printed alignment grid mated to a PCB, and more in depth technical drawings of the grid are shown in Appendix C.

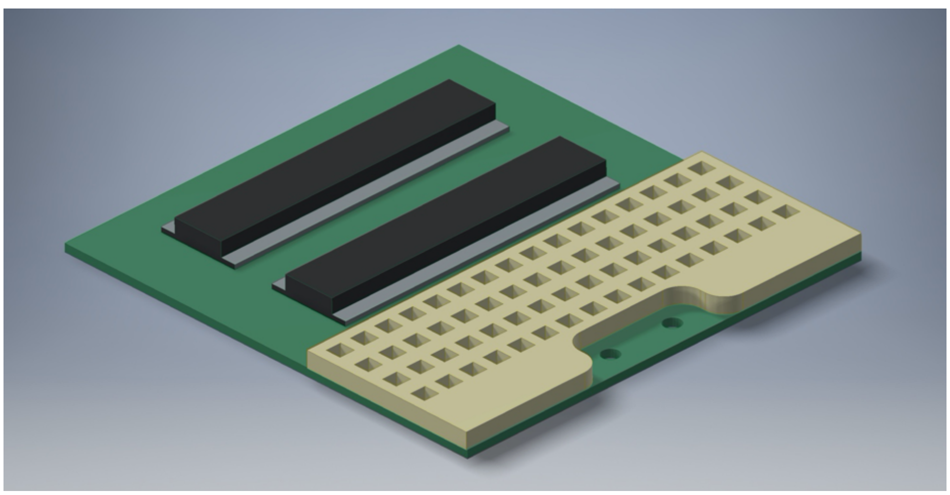


Figure 2: CAD assembly of carbon fiber aligning grid mated to CFMEA PCB

Unfortunately, due to the COVID-19 outbreak the team was never able to produce a prototype of their CFMEA to validate that the grid system would facilitate efficient electrical bonding of the 64 carbon fiber electrodes to the PCB. Thus, the design specification of 64 fully functioning channels could not be validated. Additionally, since no prototype could be produced, the team could not validate that the time to manufacture a fully functioning 64-channel board would be less than 1 hour.

Since no prototype was produced, the team could not validate that their specific boards would elicit no biological response or glial scarring around the electrodes. The Hengen Lab already has mice with single carbon fiber electrodes in-vivo for over 6 months that have not elicited any biological response. However, the team was not able to confirm that their PVA coating would avoid eliciting a biological response in-vivo.

Finally, since the team was unable to produce a prototype, they could not confirm that their design specification that the electrode array would remain functional for over 1 year in-vivo.

Overall spending (including items not actually ordered, but that the team planned to order before the COVID-19 outbreak stopped their project) totaled $1,366.59. Due to the PCB redesign, the total budget was above the team's original estimate of $730 (from progress report). However, the total cost was significantly under the $10,000 budget laid out in the design specifications (table 1).

Design Scope

As laid out in the design scope for the carbon fiber microelectrode arrays, completion of the project would include both a fully functioning carbon fiber neural recording array with up to 512 fully functioning carbon fiber recording electrodes as well as any custom tools/jigs that may be necessary in the manufacturing or construction of the arrays. Unfortunately, due to the impact of the COVID-19 outbreak, the team was unable to deliver a prototype of their CFMEA and thus did not meet their entire project scope.

The team was able to deliver a PCB that would serve as the foundation of their CFMEA. The team was also able to deliver a 3D printed grid system that they hoped would facilitate the easy and efficient electrical connection of the 64 recording carbon fiber electrodes to the PCB. Despite delivering these 2 critical components, the team never had the opportunity to test different soldering systems for electrode attachment to the PCB and thus could not design a full manufacturing system to produce functional CFMEAs. While the PCB and 3D grid were 2 critical components to a fully functioning CFMEA, the team was never able to produce a functional prototype and therefore could not meet their original design scope.

Work Required to Complete Project

With the changes made due to the COVID-19 outbreak, the project was left with multiple incomplete parts. Specifically, the team was unable to begin fabrication of the first microelectrode array that included the new circuit board. The newly designed circuit boards had been ordered to the lab when the shutdown occurred, preventing further progress on the project. Thus, there is no data validating the success of the new circuit boards in improving attachment of carbon fiber microelectrodes. Furthermore, the team had ordered a bottle of liquid 3% PVA to be used as a spray-coating for the carbon fiber microelectrodes. The team intended to spend intensive lab time coating the carbon fiber electrodes and finalizing a method to solder them to the new PCBs.

While the team simply needed to solder the electrodes to prove viability of their new PCB design, the soldering process could have introduced further complications that would need to be overcome. In particular, Dr. Hengen had warned the team that the current method of soldering, binding via silver print, would not work on the carbon fiber microelectrodes because of their difficult handling. The team had investigated multiple solder alternatives as well as procedural alternatives, such as using reflux soldering to electrically connect every electrode at once. The soldering process presents the final challenge that the team would have to complete in order to complete the project, and would have required significant hand-on lab time to determine an effective soldering process. Thus, the team would have to validate the improvements made to the new PCB, solder the carbon fiber microelectrodes to it, and confirm electrical connection to complete the project.

DesignSafe Analysis

A DesignSafe analysis was performed to identify and mitigate possible failures in the CFMEA (Appendix D). Since the CFMEA doesn't expose humans to hazards, the spreadsheet was adapted to identify and mitigate failures that would result in the loss of signal transduction through the electrode array. The three main fabrication failures were identified, and steps were established to identify and mitigate these failures as they occur. Luckily, all the failures identified will only result in slight or minimally severe situations and can be corrected fairly easily without losing too much time on fabrication.

IP Concerns

The intellectual property (IP) associated with this project will be available to the general public for further scientific progress. Dr. Hengen frequently collaborates with other researchers in the neuroscience field and would gladly share this technology with other researchers if possible. In fact, the team has exchanged emails with a few of Dr. Hengen's collaborators to discuss their work on the CFMEAs. Although Dr. Hengen is not interested in patenting the new PCBs, previous records in Lab Archives would indicate that the original idea for the changes to the circuitry came from the senior design team, preventing anyone from claiming IP.

Conclusion

Unfortunately, given the University's new policies implemented in early March due to the COVID-19 outbreak, we were unable to fully complete our intended project and solve the problem of efficiently producing a biostable carbon fiber neural recording array. Completion of our project would have included a fully functioning 64-channel carbon fiber neural recording array, with the option to stack up to 8 arrays for 512 fully functioning carbon fiber recording electrodes, as well as any custom jigs/tools that may be necessary in the manufacturing or construction of the arrays. While we had completed a design for our new PCB, designed a novel 3D printed alignment grid, communicated with manufacturers to produce our PBCs and alignment grids, we never got the opportunity to fully establish an effective and efficient system to create the electrical connection between our PCB and the electrodes. Although we were confident in our ability to complete this final aspect of our project during our remaining months in Dr. Hengen's lab, due to the University's policies regarding undergraduates in research labs, we lost the opportunity to solve this final piece of the puzzle. Since we were unable to deliver this last solution, we did not complete the project.

The work we were able to accomplish before the COVID-19 outbreak helped us meet several of our design specifications (table 2). However, since we were unable to build any prototypes, we could not verify that our solution met every design specification (table 2).

The University's new policies implemented in early March due to the COVID-19 outbreak severely impacted our ability to complete our project. Besides CAD for the alignment grid and PCB design, we had done all our work on the project in Dr. Hengen's lab where we had access to all the tools necessary to work on the electrode arrays. Unfortunately, when we returned from our Spring Break, we were informed by Dr. Hengen that we would no longer be allowed in the lab for the remainder of the semester. In a meeting with Dr. Hengen, we all decided that since we would be unable to perform any physical work, the fabrication of a prototype was unfeasible. Despite being unable to complete an actual prototype, our vision for our final microelectrode array was not significantly changed by the COVID-19 outbreak. We still see the creation on a CFMEA based on our PCB and grid design as a realistic goal and believe our solution could work. Unfortunately, we will not get to see this happen.

The future of this project is currently on hold as Dr. Hengen's lab has shut down and work is being done remotely. However, once the COVID-19 outbreak begins to wane and Dr. Hengen's lab opens up, they will begin using our new PCBs in their tetrode implantations. Unfortunately, they will likely not be using the carbon fiber microelectrodes we were working on in their implantations. Since we will no longer be working with Dr. Hengen when his lab opens up, the future of CFME technology is up in the air in the Hengen Lab. The three of us were the only people in the lab working with the 64 channel PCB carbon technology, and to continue this work, Dr. Hengen would have to pull away his other students and technicians from their important work to focus on carbon technology. Dr. Hengen voiced to us in our last meeting that this is not something he can do at the moment. We are just as disappointed as Dr. Hengen that we never had the opportunity to see our project through to completion. However, all of us are confident that carbon fiber microelectrode technology is the future of the chronic neural recording field. Hopefully there will be a time when Dr. Hengen's lab can resume where we left off and get the carbon fiber microelectrode array technology working. We are all very excited to see that day come.

The three of us learned quite a bit about carrying out a real-life project with very little guidance during the last 8 months. Over time, we learned a lot about organization, communication, and record keeping. Because of the scale of the project, it was easy to get lost in the details of one specific area of the project and lose sight of all the other important aspects of the project. The time we spent during the first month, setting up the framework of our project and dividing the project into distinct parts such as PCB design, CAD design, and fiber coatings allowed us to delegate the work and ensure all aspects of the project received consideration. Furthermore, the time we spent organizing the project in the first month helped us determine a proper time frame to stick to in order to complete the project by the end of second semester.

Over the course of the project, we also learned about the importance of communication. Communication between the 3 of us was critical in holding each other accountable for getting work done on time. Additionally, communication between our group and other individuals became very critical to our project. We had to professionally communicate with PCB design consultants, PCB manufacturers, 3D printing companies, and the lab ordering department throughout the course of the project.

A final important lesson we learned was the importance of record keeping and storing information. Professor Klaensner encouraged proper record keeping within our group from the start of Senior Design. However, it wasn't until we ran into several difficulties in the fall locating old files and documents from Dr. Hengen's lab archives and from a past senior design group that we really appreciated the importance of saving all files and notes in an organized manner.

When reflecting on the last 8 months we spent on this project, we wish we had done some things differently. We wish that we spend more time brainstorming a ground up redesign instead of adapting a current almost-working solution to work. Pretty early on in the process, we decided we would adapt the current tetrode board and technology to work with carbon. While this seemed like the safest bet at the time, now we wish we had spent a little more time brainstorming out of the box solutions that might have worked better in the end. Another thing we wish we did differently during the design/brainstorming phase was spend more time talking to and brainstorming with the different techs that work on the electrode arrays in Dr. Hengen's lab. During this phase in the fall, we really only spoke with one undergraduate student to gain perspective on the carbon electrode technology. This might have been because we were new to the lab and uncomfortable talking with the various researchers or because we thought we could solve the problem on our own, but looking back we wish we took the time to speak with more people in the Hengen lab to gain their insight on our project. The last thing we wish we had done differently was to work a little faster. Given the number of consultants and manufacturers we had to communicate with, the design and manufacturing of our PCBs and 3D printed parts took a very long time. While we weren't expected to begin prototyping until the Spring semester, we wish we had begun in the late fall of 2019 so we could have made our first prototype before Spring break.

There are no ethical considerations to claim in regards to this project. Neural implant research on small rodents has been and will continue to be performed in the Hengen lab regardless of the success of this project.

References

1. Salatino, Joseph W et al. "Glial responses to implanted electrodes in the brain." *Nature biomedical engineering* vol. 1,11 (2017): 862-877. doi:10.1038/s41551-017-0154-1

Appendix

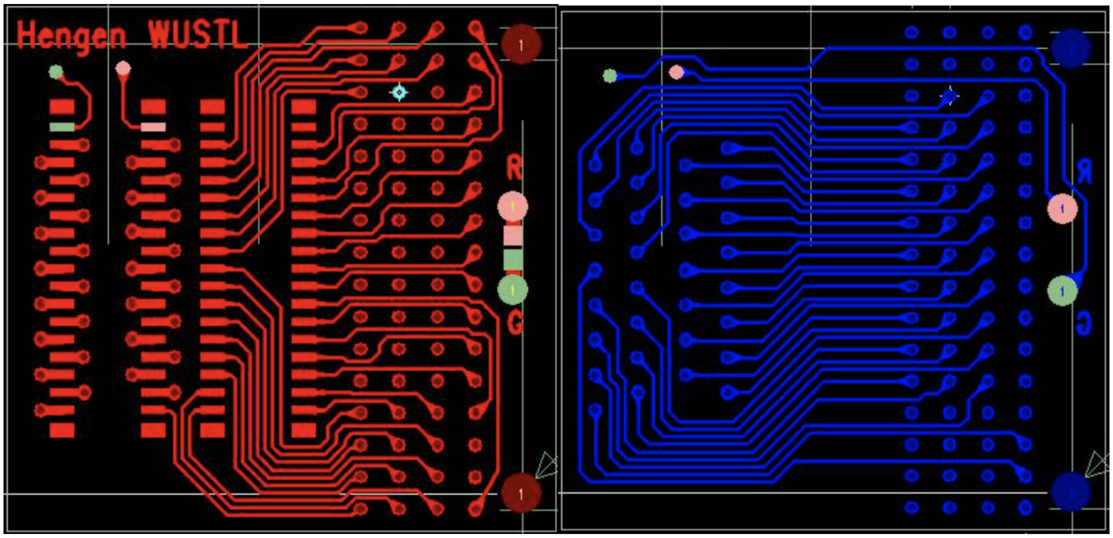
Appendix A

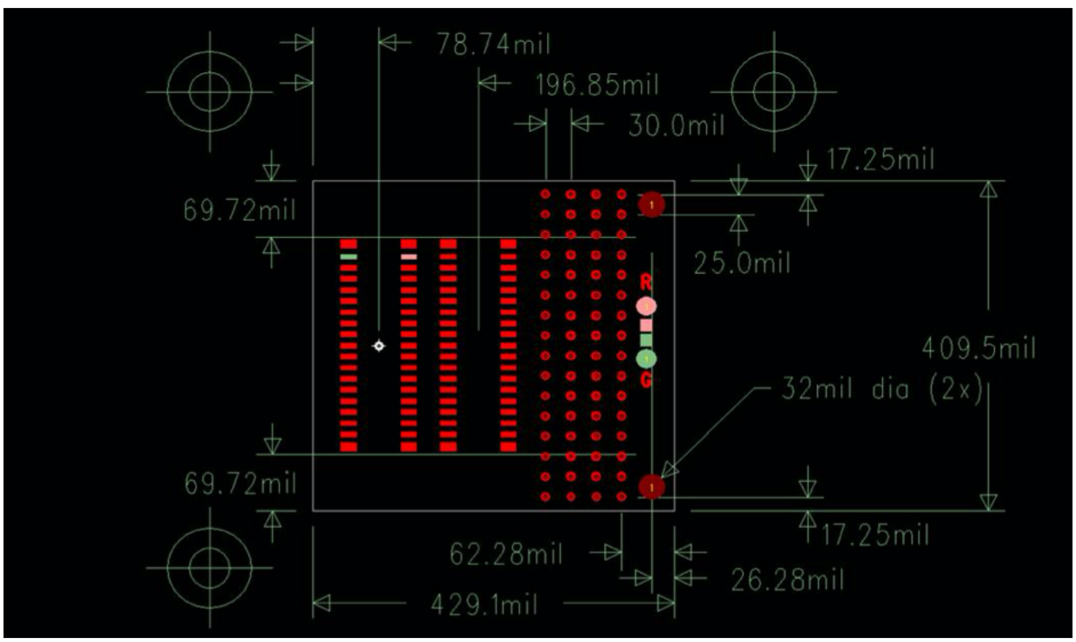
Part	Price	Source	Lead Time	Data Sheet
PCB Design	$1,045[3]	Dynamic FPC Design, Inc. 2082 Vista Valle Verde, Dr. Fallbrook, CA 92028 Phone: (760) 723-2102	4 weeks spent on redesign	N/A
PCB Manufacturing + Soldering[4]	$11.46 /unit	APT Electronics, Inc. 241 N. Crescent Way Anaheim, Ca 92801 Phone: (714) 687-6760	6 weeks	N/A
Molex Connector (P/N 504622-3412)	$0.34 /unit[5]	https://www.molex.com	1 week	http://www.literature.molex.com/SQLImages/kelmscott/Molex/PDF_Images/987651-1201.pdf
Grid	$300 /15 units[6]	Proto Labs, Inc. 5540 Pioneer Creek Dr. Maple Plain, MN 55359 United States Phone: (877) 479-3680	1 week	https://www.protolabs.com/media/1017747/microfine-green-resin-fineline.pdf
3% PVA	$9.45 /500 mL	homesciencetools.com	1 week	https://www.homesciencetools.com/content/reference/CH-PVASOLN.pdf
Total	**$1,366.59**			

Appendix A: Complete Parts list for the carbon fiber microelectrode array. Total cost includes items already ordered as well as estimates for items required to complete the prototype that weren't ordered due to COVID-19. Solder paste and silverprint were left off the list since Hengen Lab already stocks these items.

Appendix B

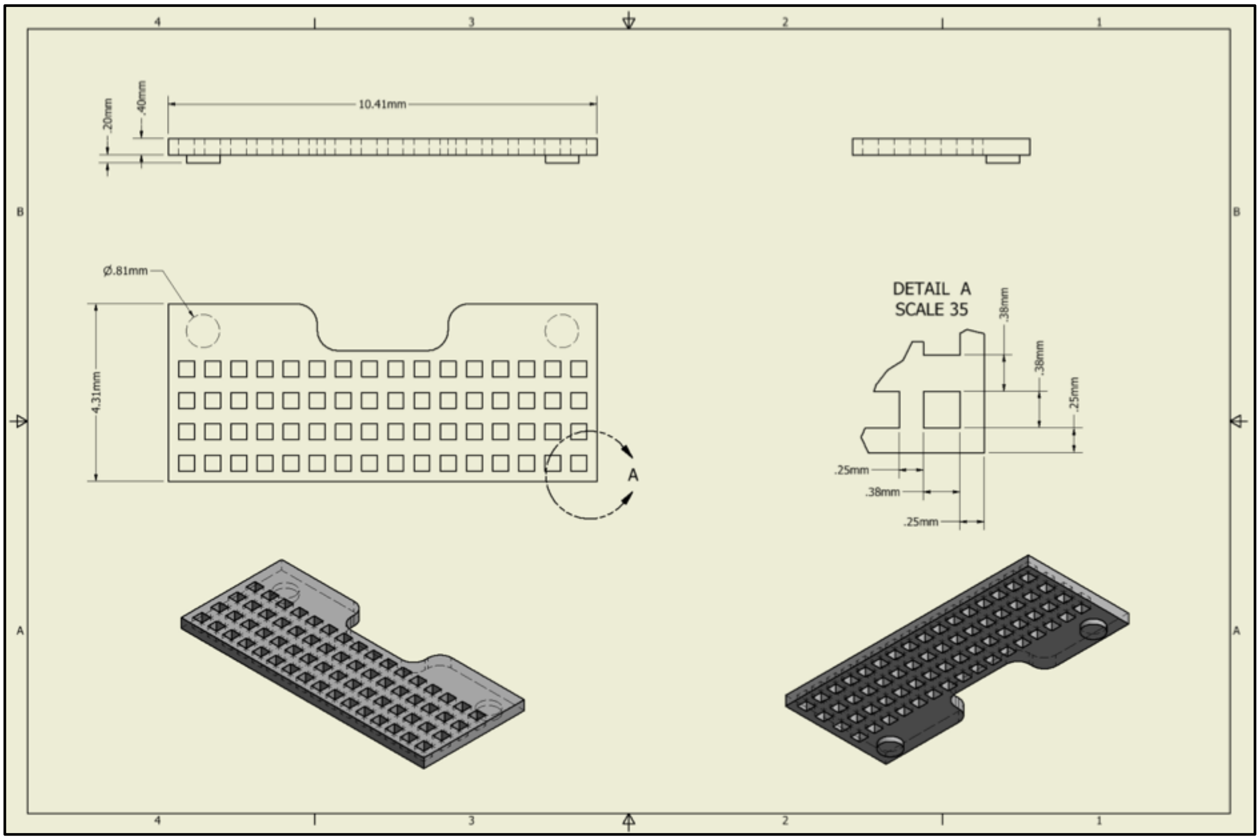
[3] Includes design fees ($595), fabrication print fees ($225), and assembly print fees ($225).
[4] APT Electronics both manufactured the PCBs and microsoldered 2 MOLEX connectors onto each board.
[5] Minimum order size of 8,000 was already purchased by Hengen Lab.
[6] Approximate cost. Order was not placed prior to suspension of on-campus work due to COVID-19.





Appendix B: Circuit diagrams for top (top left) and bottom (top right) of redesigned PCB and new spatial layout for the via grid (bottom). The traces on the PCBs simply extend a terminal of the MOLEX connectors, so no circuit diagram is included.

<u>Appendix C</u>



Appendix C: Technical drawings of 3D printed alignment grid.

Appendix D

Item	User	Task	Hazard	Cause/Failure Mode	Severity	Probability	Exposure	Risk Level
1	Fabricator	Produce PCB	Faulty PCB	Bridged Pads, Incomplete vias, misprinting	1	2	1	2
2	Technician	Connect Electrodes to PCB	Faulty electrode-PCB connection	No signal transduction	2	3	1	6
3	Technician	Monitor Implant	Loss of signal in 1 electrode	Broken electrode, loose connection, encapsulation response	1	2	1	2

Item	Method of Risk Reduction/Mitigation	Severity	Probability	Exposure	Risk Level	Person Responsible	Date	Comments
1	Select Different PCB	1	1	1	1	David Jones	4/13/20	We ordered 500 PCBs so we are expecting that a few will be faulty. Faulty PCBs can be determined through visual inspection or electrical testing. Faulty MOLEX connectors are also a possibility, but much less likely.
2	Add more solder paste. Or scrap and build another Electrode array	1	1	1	1	David Jones	4/13/20	We don't expect every electrode to be connected properly 100% of the time. Luckily, faulty connections can be determined by electrical testing and can be corrected before implantation into a mouse.
3	Ensure connections are good before implantation.	1	2	1	1	David Jones	4/13/20	Unfortunately, loss of signal in one or more electrodes is common over a long period of time. As the mouse shakes its head and moves around, the CFMEA wears down and electrical connections can become loose.

Appendix D: DesignSafe Analysis spreadsheet. Since the carbon fiber microelectrode array doesn't expose humans to hazards, the spreadsheet was adapted to identify and mitigate failures that would result in the loss of signal transduction through the electrode array.