Anapad

The Next-Generation Computer Interface

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***Abstract*—The Model A anapad is our vision for the next-generation computer interface. An anapad is a new kind of hardware interface that synthesizes the functionality of the keyboard and mouse into a single device. The first-generation anapad we've created is called Model A. Touch sensors, force sensors, and localized haptic impulses all combine to mimic the feeling of pressing keys on a physical keyboard. Unlike existing computer interfaces, an anapad dynamically adapts to any computing task, all while staying directly beneath your fingertips. For power users of desktop computers, the Model A anapad will provide a more efficient, seamless, and enjoyable user experience compared to the traditional peripherals.**

I. Introduction

THE computer keyboard and mouse has been the predominant hardware interface for desktop computers for over six decades. Technology has progressed dramatically over the years, but the way we interface with computers has largely remained the same. We envision a new kind of hardware interface that synthesizes the functionality of the keyboard and mouse into a single device. The device will consist of a display mounted in a streamlined housing that approximates the footprint of a traditional keyboard. As we imagine how to innovate the desktop environment for greater productivity, intuition, and satisfaction, the aim of our device is to provide a more efficient, seamless, and enjoyable user experience.

With such a device, we endeavor to define a new device class. If the device is no longer solely a keyboard or a tracking device, what will it be called? The technical term is *anapad*, from the Greek $\alpha\nu\alpha$—transliterated *ana*—meaning "upward," and *pad*, which describes the form factor of the device.

The first-generation anapad we've created is called Model A. We've built Model A using modern technologies and advanced engineering techniques, giving the user an intuitive and seamless experience. This experience includes a "plug and play" model which will allow a user to plug Model A into any computer and immediately get to work. By using the preexisting USB Human Interface Devices (HID) protocol, a user can use both the virtual keyboard and trackpad on Model A without the need to install an operating system driver. Additionally, Model A implements an array of 33 linear resonant actuators (LRAs) to provide haptic feedback in response to user input. The lack of tactile feedback on a touchscreen makes it more difficult to type efficiently and quickly compared to a traditional mechanical keyboard so an LRA array is used to mitigate this problem. The LRA array induces vibrations in the proximity of a user's touch to create localized haptic impulses. Furthermore, Model A features four symetically arranged load surfaces. When a user depresses the top panel, the load surfaces precisely capture the applied force using strain gauges and high resolution analog-to-digital converters. This creates a localized force sensor that is used to deter erroneous taps and gestures the user may accidentally trigger and to add an extra dimension to user input.

II. Background

The anapad is a response to changing circumstances in global culture and technology. The overarching cultural change that has prompted the anapad is the ever-broadening role of personal computers in the workplace. The late twentieth century saw the advent of personal computers as the primary instrument of knowledge workers and as the tool that has impacted virtually every industry ever since. The transition to this new paradigm has continued until the present day, and recent circumstances have caused it to accelerate. The coronavirus pandemic of 2020 prompted the expansion of remote work as many businesses realized they could sustain their operations through digital communication while workers stayed at home. As remote work has increasingly replaced on-site work—including meetings, presentations, interviews, and so on—the role of the personal computer has broadened even further.

It appears the ever-broadening role of personal computers in the workplace has engendered dissatisfaction with traditional computer interfaces, even prior to the pandemic. The most recent decade has seen the advent of tablet computers, touch-screen laptops, "ergonomic" peripherals and similar developments, all of which aim to modify or augment the traditional computer interface. We believe these developments reflect a widespread cultural shift in thinking about what computers can be, what they can do, and how we can interface with them. This cultural shift is a prime opportunity to innovate the computer interface.

Opportunities to innovate the computer interface have also been afforded by changes in technology. The key enabling technologies that make the anapad possible include flat panel displays, single board computers (SBC), and haptic devices. In the recent decade, all three of these technologies have undergone rapid development and reduced cost. Modern flat panel displays are now thin enough and sufficiently economical to enable the form factor and market feasibility of an anapad. Similarly, modern SBCs are now sufficiently powerful and economical to enable rich, on-board graphics processing in small-scale devices such as an anapad. Modern haptic devices include LRAs, which compared to their predecessors enable richer and more precise haptic feedback. We believe these key enabling technologies afford a timely opportunity to introduce the anapad as the next-generation computer interface.

III. Related Works

Throughout the decades there have been a number of attempts to innovate the functionality of the computer interface. Here we discuss some of the most interesting and relevant examples.

A. Combining Peripherals

The most significant innovation an anapad makes is enabling a user to have a dynamic computer interface directly underneath their fingertips. This means that the peripherals used to interface with an individual's desktop computer can be synthesized into a single device. A past attempt to implement such an innovation was executed by Lenovo's ThinkPad laptop. An iconic red-colored "trackpoint" resides in the center of the laptop's keyboard providing the user with an analog control stick to operate the operating system's cursor. This enables the user to transition between typing and cursor movement relatively seamlessly due to the two inputs (keyboard and trackpoint) residing in close proximity to the user's fingertips during normal usage. However, the trackpoint presents a couple of problems. Namely, the trackpoint itself is relatively small, likely to prevent its size from disrupting the footprint of the surrounding keys. This can make it difficult for the user to locate the trackpoint with their finger without looking at the keyboard. Additionally, it can be quite cumbersome to use due to its high sensitivity. Lenovo continues to produce ThinkPad laptops with the trackpoint feature up to the present day.

In 2018 Asus Computer Inc. unveiled an attempt to combine a numpad with the built-in trackpad of a laptop. The updated Asus ZenBook introduced the NumberPad, a feature which can be toggled by tapping its symbol in the corner of the trackpad. When activated, NumberPad appears as an illuminated numpad superimposed on the built-in trackpad; when deactivated it disappears completely, leaving the trackpad to appear as normal. Asus described the feature as a solution to the lack of a physical numpad on compact laptops. As of the time of writing, NumberPad remains a feature of the most recent generation of ZenBook.

B. Enhancing Functionality

Some personal computer firms have attempted to enhance functionality by blurring the lines between typical form factors. The recent decade saw the advent of touchscreen laptops, which implemented tablet-like functionality in the traditional laptop form factor. Some touchscreen laptops even implemented a 180-degree hinge so the device could be transformed and then handled as though it were a tablet. Some prominent examples of commercial touchscreen laptops include the Microsoft Surface product family and the Lenovo Yoga product family. Such devices made it possible to use the simple and flexible interface of touch input in the context of preexisting desktop-class applications. This new functionality came at the expense of making the laptop form factor more complicated and arguably more cumbersome to use. The use of touch input for preexisting desktop-class applications is anachronistic, whereas touch input from an anapad will have been designed specifically for the desktop environment.

Some attempts have been made to improve the performance of the computer keyboard by making new key layouts. The ubiquitous QWERTY layout has been the prevailing standard since the age of mechanical typewriters of the late nineteenth century. In recent times, researchers and enthusiasts have invented alternative key layouts that improve overall typing speed such as Dvorak, Colemak, and QGMLWY. With an anapad, there is the potential to offer infinite configurability of key layouts to suit user needs, whether for improved performance or otherwise.

Some attempts have been made to enhance the functionality of existing computer interfaces by using touch pressure as an additional input dimension. In 2014, Apple Inc. unveiled Force Touch technology which enabled touch surfaces to distinguish between two levels of touch pressure. For instance, the technology was implemented in the built-in trackpads of the MacBook product line and in the Magic Trackpad 2 peripheral. The Force Touch feature of Apple trackpads enabled functionality such as new application shortcuts and pressure-sensitive drawing. It is interesting to note that while Force Touch was also implemented in other products such as iPhone and Apple Watch, as of the time of writing it has been discontinued in all products except for the Mac product family. This development suggests that whereas touch pressure sensing may not be a useful feature in the context of mobile devices, it is indeed a useful feature in the desktop environment.

In 2016, Apple attempted to augment existing keyboard designs by introducing the Touch Bar in MacBook Pro. The Touch Bar is a slender multicolor touch display that replaces the function row on a traditional keyboard. The intention behind the Touch Bar is clear: to make the keyboard more dynamic and configurable as well as adaptive based on context. The Touch Bar enabled new functionality for the keyboard such as typing suggestions, audio and video scrubbing, and application-specific controls. The intention to make the keyboard more dynamic, configurable, and adaptive is closely aligned with the concept of an anapad. However, it is important to note that as of the time of writing the Touch Bar is no longer included in the most recent generation of MacBook Pro. This development suggests that the Touch Bar was not a successful feature as it possibly did not improve the user experience for MacBook Pro customers. This inference, if true, has enormous implications for the design of the anapad. Perhaps the Touch Bar was not an improvement because, due to its dynamic nature, it created an unhealthy tension between itself and the main display of the computer. In the design of the anapad, we must take care to manage the tension between the anapad display and the main display. To effectively manage the tension may mean that the dynamic elements of the anapad are carefully constrained so as not to distract the user from the main display.

C. Feedback

An important feature of the anapad is that it emulates the tactility of a traditional mechanical keyboard on a touchscreen. A study conducted at Purdue University analyzed the typing performance of 12 participants subjected to various keyclick feedback methods on a zero-travel computer keyboard [1]. A zero-travel keyboard consists of a computer keyboard with keys that do not travel, that is, the keyboard is completely flat. The following four keyclick feedback methods were used: localized haptics, global haptics, auditory feedback, and no feedback. The researchers used the following three metrics to quantify the keyclick feedback efficiency: words per minute (WPM), keystroke per character (KSPC), and total error rate. The WPM metric is simply the words typed per minute by the participant. The KSPC is the ratio of the input string length to the transcribed text length. And the total error rate is the ratio of the total incorrectly typed characters to the total typed characters (either incorrectly or correctly typed). The researchers concluded with strong statistical evidence that, when using a zero-travel keyboard, the participants performed best on all the metrics when using a localized haptic feedback, with global haptic feedback and auditory feedback following respectively. There was a relatively small difference between the metric performance of a typist with a localized haptic feedback keyboard versus a traditional mechanical keyboard. This conclusion is significant because the anapad will restore the tactility of a mechanical keyboard by providing localized haptics via an LRA array and audio feedback via an integrated stereo speaker system.

There are several ways to implement localized haptics on a device such as an anapad. Researchers at the University of British Columbia and Northwestern University explored and analyzed several programmable haptic feedback methods that can be implemented on flat surfaces. They noted that "the range and quality of the haptic sensations which can be produced vary with the latency, bandwidth, and strength of the actuator used, from the ubiquitous but crude eccentric-mass vibrating motor to more expressive piezoelectric actuators" [2]. Additionally the researchers stated, "Vibrations are also effective at producing transient events such as the detent of a button press" [2]. Such vibrations the researchers are referring to are achievable using the z-axis LRA array on an anapad. By varying the latency, bandwidth, and strength of the vibration the LRAs produce, another dimension of user feedback is possible, making the user experience on an anapad much more intuitive.

It is our expectation that a user will experience a smooth transition from a mechanical keyboard to an anapad because of our great efforts to give ample and effective feedback to the user.

IV. Results

We successfully constructed two production-level Model A prototypes. Fig. 1 depicts the two fully assembled Model A anapads side by side. The process of fabricating these two prototypes and the technical details of Model A's technology is discussed in the following sections.

Fig. 1: Two fully assembled Model A anapads.

A. Process

We met daily over the summer and fall semesters of 2022. A workspace depicted in Fig. 42 was used to work in during this time. At the beginning of the summer, experimentation and brainstorming regarding anapad features ensued. Then we transitioned to conceptualizing these experiments and ideas in the middle of the summer. Finally, implementing the Model A anapad took place towards the end of the summer and all of fall. Fusion 360 was used as the CAD tool for modeling and designing Model A's mechanical designs and electrical designs. Integrated Development Environments (IDEs) such as uVision and IntelliJ IDEA were used to aid in programming experiments and Model A's firmware. Local and remote machine shops and manufacturing plants were used to fabricate our hardware components.

Our project website is available here [3]. Our code repositories are organized under a GitHub Organization and are available here [4].

We've created a video demonstrating and documenting Model A's functionality and design. The video is available here.

B. System Overview

Fig. 2 shows the system overview of Model A. The following sections will illuminate the details of each subsystem.

C. Hardware

Model A consists of several vertically stacked functional layers. Fig. 3 and Fig. 4 show exploded views of the Model A assembly that reveal the functional layers. Fig. 5 is an exploded side view of the assembly that shows the order of the functional layers. Each layer fits compactly with adjacent layers to achieve an overall slim form factor.

The functional layers combine to form four subassemblies: the enclosure, the motherboard assembly, the haptics board, and the display assembly. Each subassembly is described as follows.

1) Enclosure: As shown in Fig. 6, the enclosure consists of a CNC-milled aluminum body and a laser-cut baseplate, each with a bead blast finish. A total of six SLS 3D printed internal structures are adhered to the aluminum body and baseplate

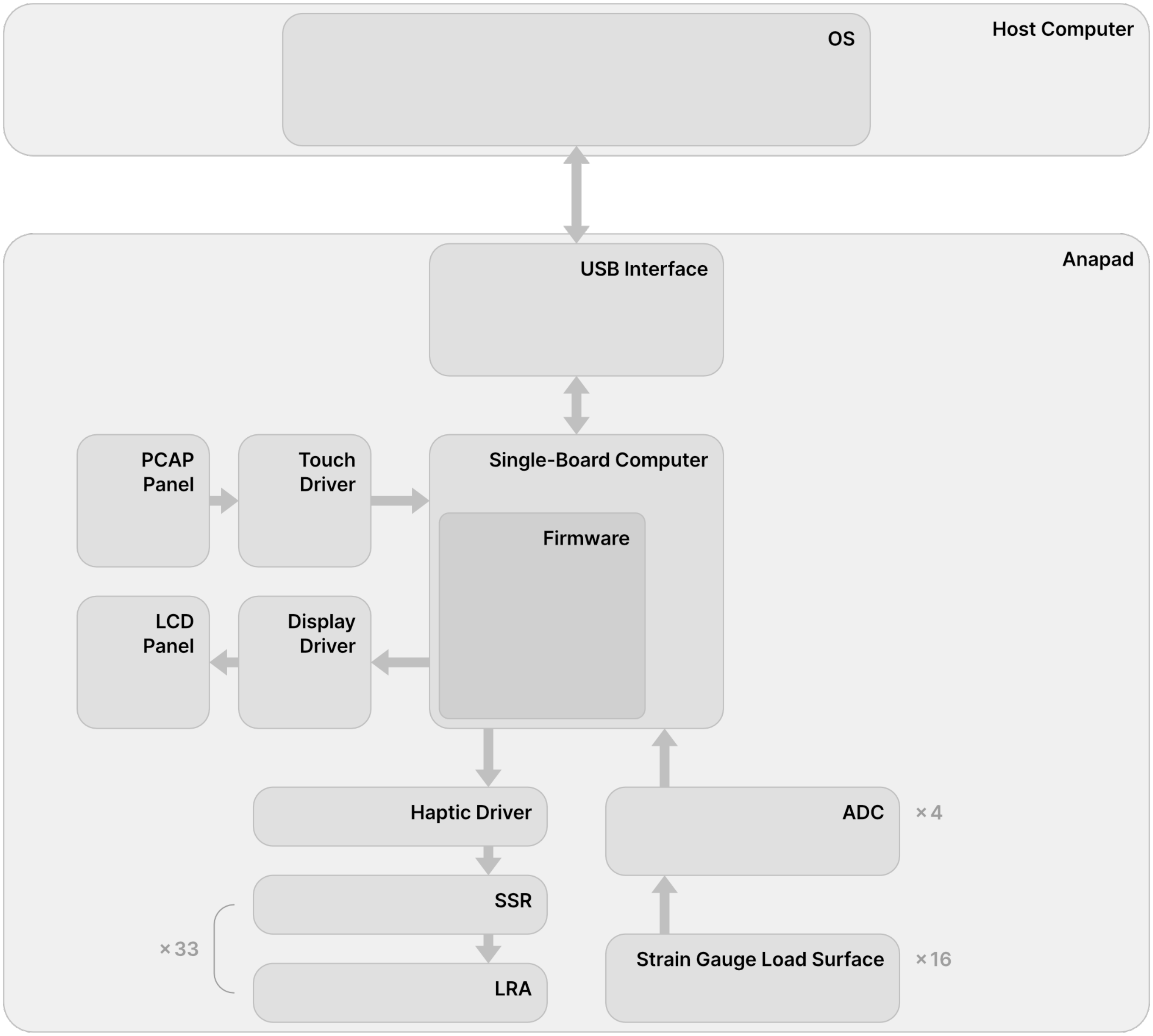

Fig. 2: The Model A system overview.

using a cold weld epoxy solution. These internal structures provide mechanical support for the internal components and mounting points for the baseplate.

The baseplate, also shown in Fig. 7, exposes six rubber feet, four fasteners, and a vinyl inscription of the anapad icon.

2) Motherboard Assembly: The motherboard assembly consists of three daughter boards and one motherboard. The display driver is a daughter board that drives the display via HDMI. The projective capacitive, or PCAP, touch panel driver is a daughter board that drives the touch panel and can sense up to ten touches. The Raspberry Pi Compute Module 4 is a daughter board that is a single board computer responsible for running the firmware and interfacing with all the other hardware components. A micro SD card is used as the non-volatile storage medium. Four load surfaces are symmetrically arranged to precisely measure the force applied by a user's touch. Each load surface consists of four strain gauges configured in a Wheatstone bridge and one high resolution analog-to-digital convertor. Finally, a USB-C connector is used to supply power and provide data transmission. Fig. 8 and Fig. 9 depict the motherboard assembly top and bottom sides respectively.

3) Haptics Board: The haptics board contains 33 linear resonant actuators, or LRAs, that vibrate along the z-axis to provide localized haptic impulses to a user's fingertips. Each LRA is controlled by a metal oxide semiconductor, or MOS-based, solid state relay, or SSR, which allows the firmware to control each LRA independently. These LRAs are driven by a haptic driver and the SSRs are switched using IO port expanders. The haptics board interfaces with the motherboard through a flexible printed circuit cable, or FPC. Fig. 10 and Fig. 11 depict the haptics board top and bottom sides respectively.

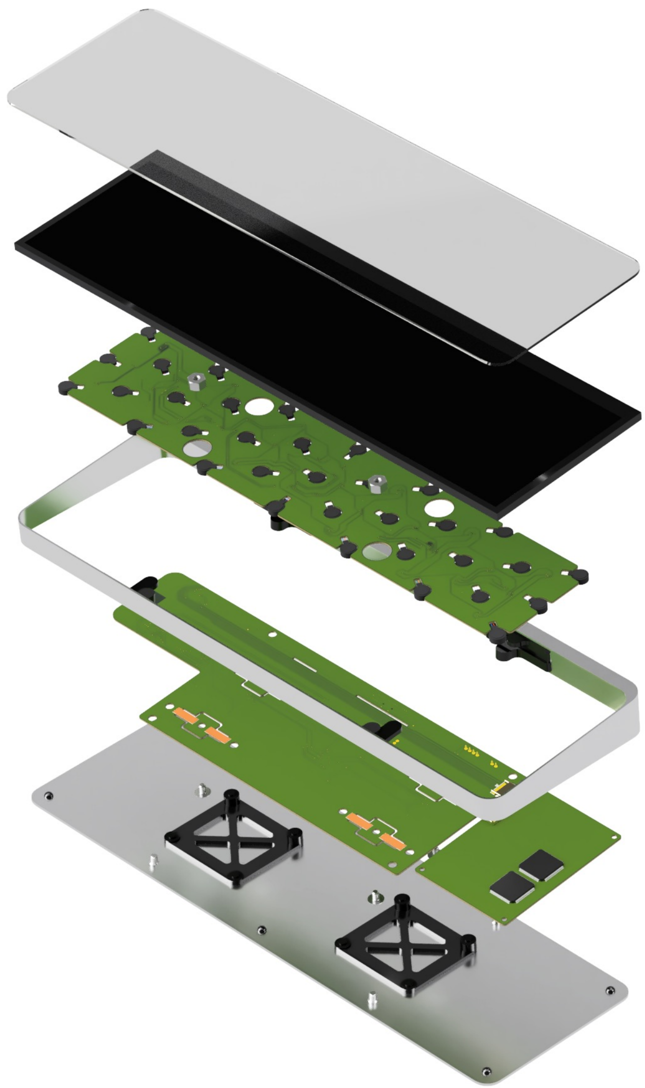

Fig. 3: An exploded top view of the Model A anapad.

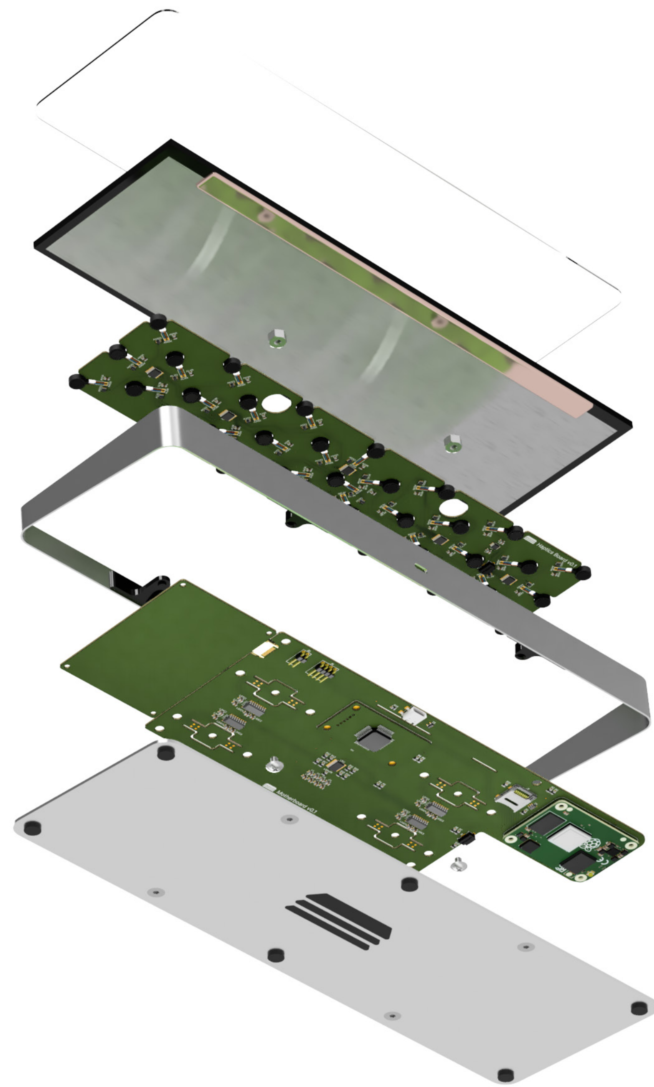

Fig. 4: An exploded bottom view of the Model A anapad.

4) Display Assembly: The display assembly, shown in Fig. 12, consists of a stretch LCD panel, a PCAP touch panel, and a non-glare top panel adhered with liquid optically clear adhesive. Four threaded standoffs are adhered to the back of the display panel using a cold weld epoxy solution and are used to internally mount the display assembly as well as to transfer force from user input to the load surfaces. As shown in Fig. 13, the haptics board is adhered to the back of the LCD panel to provide localized haptic impulses to a user's fingertips on the top panel.

5) Device Bridge: An intermediary component called the device bridge is connected to Model A to supply power and to facilitate USB data transmission; see Fig. 14 and Fig. 15. A DC power jack is used to connect the device bridge to a five volt power supply and two USB connectors are used to connect Model A to a host computer. As shown in Fig. 16, the internal components of the device bridge are housed in a stereolithography 3D printed enclosure.

D. Bill of Materials

Our Bill of Materials (BOM) is shown in the appendix of this report. The BOM for the Model A assembly is contained in Fig. 24. The BOM for the haptics board is contained in Fig. 25. The BOM for the motherboard is contained in Fig. 26. Finally, the BOM for the device bridge assembly and electronics is contained in Fig. 27.

E. Firmware

We've created a number of demonstrations accessible through the firmware that show the hardware capabilities of Model A. Fig. 17 and Fig. 18 show the demo firmware keyboard views in light and dark color themes respectively. Model A presents a virtual split keyboard for improved typing

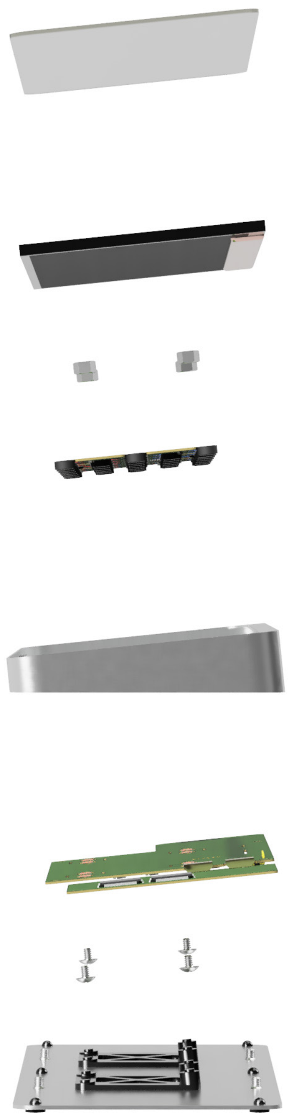

Fig. 5: An exploded side view of the Model A anapad.

ergonomics and an updated keyboard layout for improved typing efficiency.

Fig. 19 and Fig. 20 show the demo firmware trackpad views in light and dark color themes respectively. When a user's finger moves across the keys, a virtual trackpad seamlessly appears beneath the user's fingertips. Tapping outside the virtual trackpad returns the user to the keyboard.

Fig. 22 captures a moment from a firmware demonstration that visualizes the user's touches on the touch panel as well as shows the wide color gamut of the display using a beautiful color gradient.

Fig. 23 captures a moment from a firmware demonstration that visualizes the localized measurements of the four load surfaces. The greater the force applied by a user's touch, the larger the blue circles appear. The blue rectangle in the center depicts the average of the four load surface measurements.

Fig. 21 captures a moment from a firmware demonstration that visualizes the touch sensing, force sensing, and localized haptic feedback. Underneath every red circle is an LRA that vibrates when it is close enough to a user's touch. The vibrational amplitude of the LRAs surrounding a touch is proportional to the applied force. The haptic sensations delivered by the vibrating LRAs is localized due to the direct mechanical coupling between a user's touch and the surrounding LRAs.

References

[1] J. R. Kim and H. Z. Tan, "A Study of Touch Typing Performance with Keyclick Feedback," in *2014 IEEE Haptics Symposium (HAPTICS)*, 2014, pp. 227–233.

[2] V. Lévesque, L. Oram, K. MacLean, J. E. Colgate, and M. A. Peshkin, "Restoring Physicality to Touch Interaction with Programmable Friction," in *2011 IEEE International Conference on Consumer Electronics (ICCE)*, 2011, pp. 61–62.

[3] The Anapad Team, "The Anapad Website," Online (2022).

[4] ——, "The Anapad Team Github Organization," Online (2022).

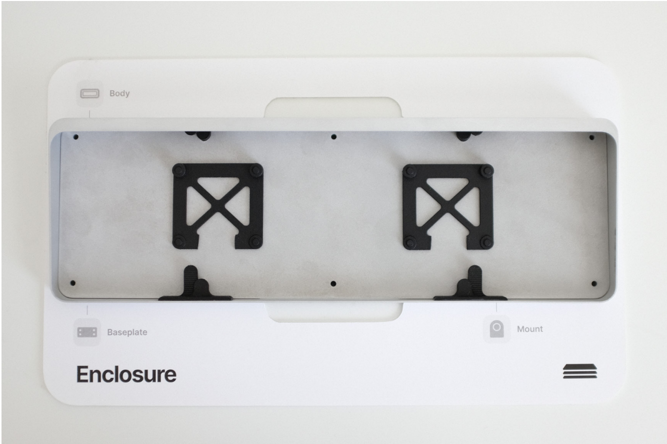

Fig. 6: The enclosure.

Fig. 7: Bottom view of the enclosure.

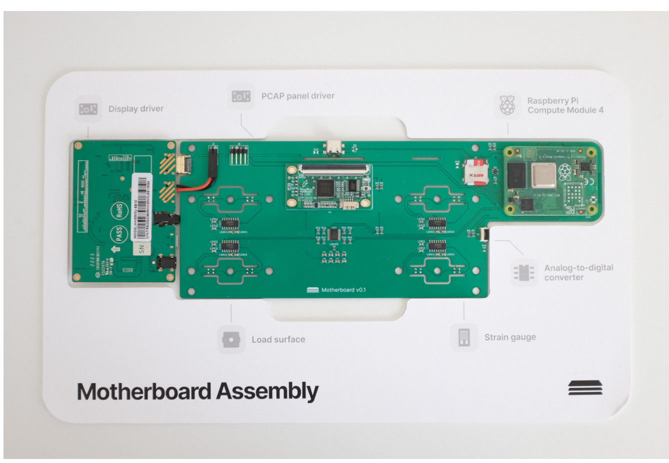

Fig. 8: The motherboard assembly.

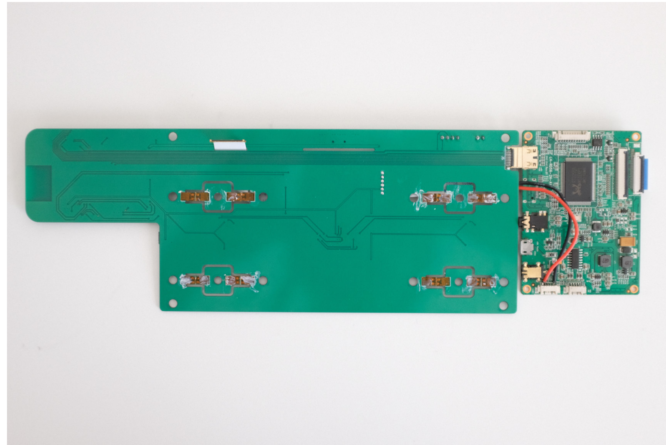

Fig. 9: Bottom view of the motherboard assembly. Note the placement of the strain gauges on the load surfaces.

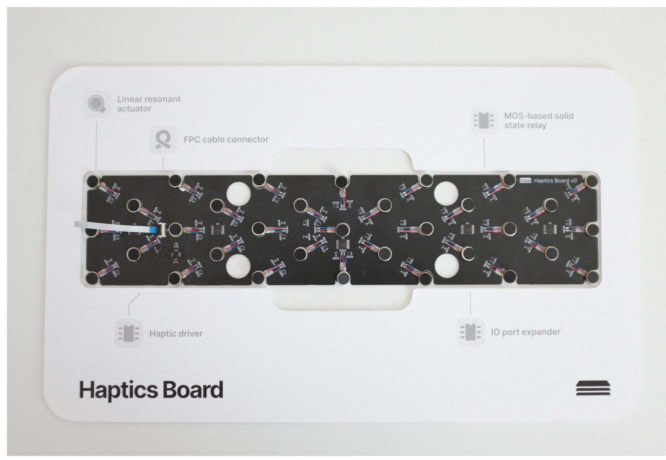

Fig. 10: The haptics board.

Fig. 11: Bottom view of the haptics board.

Fig. 12: The display assembly.

Fig. 13: Bottom view of the display assembly. Note that a haptics board has been applied.

Fig. 14: Top view of the device bridge.

Fig. 15: Bottom view of the device bridge.

Fig. 16: Disassembly of the device bridge showing the power board, USB board, and enclosure.

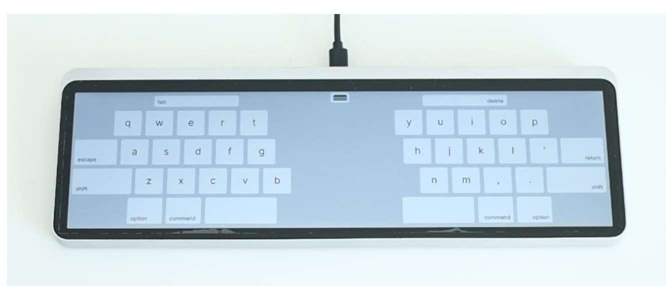

Fig. 17: The demo firmware keyboard view with the light color theme.

Fig. 18: The demo firmware keyboard view with the dark color theme.

Fig. 19: The demo firmware trackpad view with the light color theme.

Fig. 20: The demo firmware trackpad view with the dark color theme.

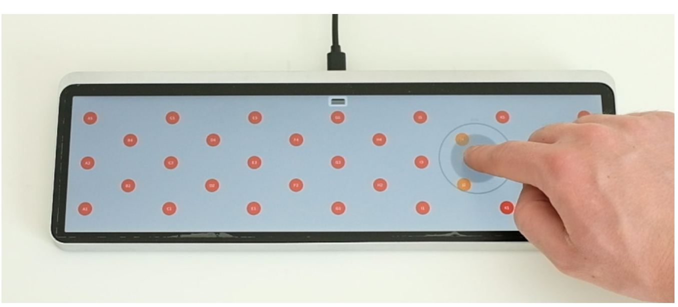

Fig. 21: The demo firmware "force haptics" view.

Fig. 22: The demo firmware "touches" view.

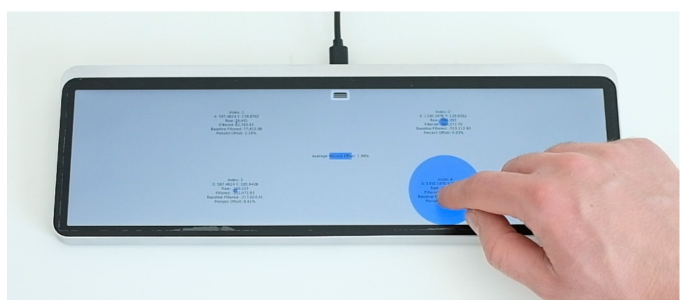

Fig. 23: The demo firmware "load surfaces" view.

Appendix

Description	Manufacturer	Part Number	Quantity	Unit Price	Total Price
LCD panel with PCAP panel and eDP cable	BOE	NV126B5M-N42	1	$109.23	$109.23
Display driver daughter board	Unknown	Unknown	1	$36.15	$36.15
PCAP panel driver daughter board	Unknown	GT9110 Board	1	$36.48	$36.48
Raspberry Pi Compute Module 4 Lite SBC daughter board	Raspberry Pi	Compute Module 4 Lite (CM4x0x000)	1	$35.00	$35.00
Haptics board	Anapad Team	v0.1	1	$30.19	$30.19
Motherboard	Anapad Team	v0.1	1	$56.10	$56.10
J-B Weld two part cold weld epoxy solution	J-B Weld	N/A	1	$7.52	$7.52
M4 × 6 mm countersink bottom plate screws	McMaster-Carr	92125A186	4	$0.11	$0.44
6-32 × 3/16″ truss head threaded standoff screws	McMaster-Carr	91770A143	4	$0.06	$0.24
6-32 × 3/16″ hex threaded standoffs	McMaster-Carr	91780A445	4	$1.05	$4.20
5/16″ OD Durometer 60A press-fit bumper feet	McMaster-Carr	9309K33	6	$0.23	$1.38
32 GB micro SD card	Lexar	E-series microSDHC card 32 GB	1	$5.24	$5.24
10 ml bottle of liquid optically clear adhesive (LOCA)	N/A	N/A	1	$3.75	$3.75
Matte black acrylic paint	Blick Art Materials	N/A	1	$2.65	$2.65
24 AWG wires with crimped pin headers	N/A	N/A	2	$0.50	$1.00
Anapad icon inscription vinyl	Anapad Team	v1	1	$0.04	$0.04
Semi-gloss acrylic top panel	Anapad Team	v1	1	$6.13	$6.13
USB Type A to USB Type C 6ft cable	ZUKUN	N/A	1	$9.64	$9.64
USB Type A to USB Type A 3ft cable	Monoprice	105442	1	$4.67	$4.67
5V 5A (25W) Power Supply AC/DC Power Adapter	JOVNO	N/A	1	$18.22	$18.22
Enclosure metal body	Anapad Team via Xometry	v1	1	$154.79	$154.79
Enclosure metal baseplate	Anapad Team via Xometry	v1	1	$118.92	$118.92
Enclosure SLS 3D printed bracket back left	Anapad Team via Xometry	v0.1	1	$8.21	$8.21
Enclosure SLS 3D printed bracket back right	Anapad Team via Xometry	v0.1	1	$7.38	$7.38
Enclosure SLS 3D printed bracket front left	Anapad Team via Xometry	v0.1	1	$8.00	$8.00
Enclosure SLS 3D printed bracket front right	Anapad Team via Xometry	v0.1	1	$8.00	$8.00
Enclosure SLS 3D motherboard base	Anapad Team via Xometry	v0.1	2	$11.04	$22.08

Fig. 24: The assembly bill of materials.

Description	Manufacturer	Part Number	Quantity	Unit Price	Total Price
Haptic driver IC	Texas Instruments	DRV2605LDGSR	1	$3.63	$3.63
Linear Resonant Actuator (LRA)	NFP Motor	ELV0832B-205Hz	33	$0.88	$29.04
FPC connector	Molex	505110-0692	1	$0.70	$0.70
FPC ribbon cable	Molex	15166-0054	1	$2.57	$2.57
Dual channel N-channel MOSFET IC	Rohm Semiconductor	UM6K31NTN	33	$0.31	$10.23
8-bit I2C GPIO port expander IC	Texas Instruments	TCA9534PWR	5	$1.30	$6.48
30kΩ 1% 0805 SMD resistor	Stackpole Electronics	RMCF0805FT30K0	33	$0.02	$0.79
1μF 0805 SMD capacitor	Samsung Electro-Mechanics	CL21B105KAFNNNE	2	$0.07	$0.13
Haptics Board v0.1 PCB	Anapad Team via JLCPCB	v0.1	1	$2.53	$2.53

Fig. 25: The haptics board bill of materials.

Description	Manufacturer	Part Number	Quantity	Unit Price	Total Price
FPC connector	Molex	505110-0692	1	$0.70	$0.70
Mini HDMI male plug connector	Unknown	Unknown	1	$1.00	$1.00
24-bit ADC	Nuvoton	NAU7802	4	$1.54	$6.15
Strain gauge	Unknown	BF350-3AA	16	$0.43	$6.88
USB 2.0 Type C female connector	GCT	USB4110	1	$1.34	$1.34
SD card female connector	GCT	MEM2067-02-180-00-A	1	$1.14	$1.14
PCB connector receptacle, 100 pin, 0.4mm pitch	Hirose	DF40C-100DS-0.4V	2	$2.46	$4.92
Dual-channel ESD suppressor	Texas Instruments	TPD2E2U06-Q1	1	$0.61	$0.61
Power switch IC	Richtek	RT9742GGJ5	1	$4.03	$4.03
4-channel I2C multiplexer	Texas Instruments	TCA9544APWR	1	$1.77	$1.77
330pF 0805 SMD capacitor	Wurth Elektronik	885012207083	4	$0.10	$0.40
1μF 0805 SMD capacitor	Samsung Electro-Mechanics	CL21B105KAFNNNE	8	$0.07	$0.52
0.1μF 0805 SMD capacitor	Samsung Electro-Mechanics	CL21B104KACNNNC	12	$0.04	$0.44
10kΩ 5% 0805 SMD resistor	Stackpole Electronics	RMCF0805JT10K0	2	$0.02	$0.04
2.2kΩ 1% 0805 SMD resistor	Stackpole Electronics	RMCF0805FT2K20	16	$0.02	$0.38
0Ω 0805 SMD resistor	Stackpole Electronics	RMCF0805ZT0R00	3	$0.10	$0.30
1 row, 2 count, 90-degree male pin header	Adam Tech	PH1RB-02-UA	1	$0.10	$0.10
1 row, 4 count, 90-degree male pin header	Adam Tech	PH1RB-04-UA	1	$0.18	$0.18
Motherboard v0.1 PCB	Anapad Team via JLCPCB	v0.1	1	$2.79	$2.79

Fig. 26: The motherboard bill of materials.

Description	Manufacturer	Part Number	Quantity	Unit Price	Total Price
SLA 3D printed enclosure	Anapad Team via Xometry	v0.1	1	$125.25	$125.25
M4 × 0.70 mm screws	McMaster-Carr	91294A192	1	$0.06	$0.06
DC power jack female connector	CUI Devices	PJ-202AH	1	$0.79	$0.79
Power Board v0.1 PCB	Anapad Team via JLCPCB	v0.1	1	$0.71	$0.71
24 AWG insulated wire	N/A	N/A	2	$0.10	$0.20
USB Board v0.1 PCB	Anapad Team via JLCPCB	v0.1	1	$1.11	$1.11
USB Type A female connector	GCT	USB1046	2	$0.75	$1.50
0Ω 0805 SMD resistor	Stackpole Electronics	RMCF0805ZT0R00	2	$0.10	$0.20

Fig. 27: The device bridge bill of materials.

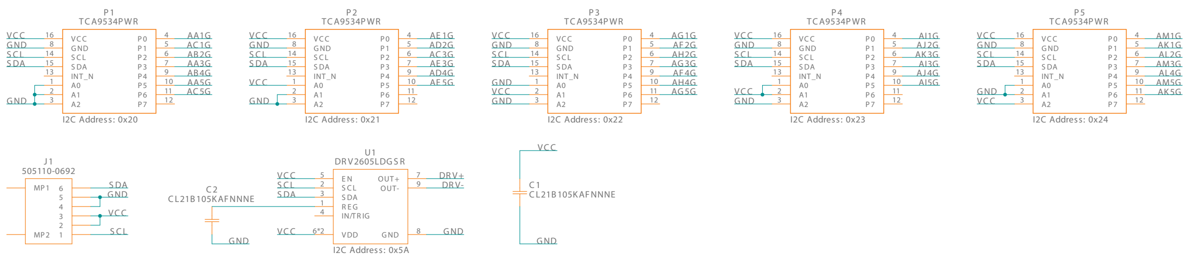

Fig. 28: The haptics board schematic “I2C Interface” sheet.

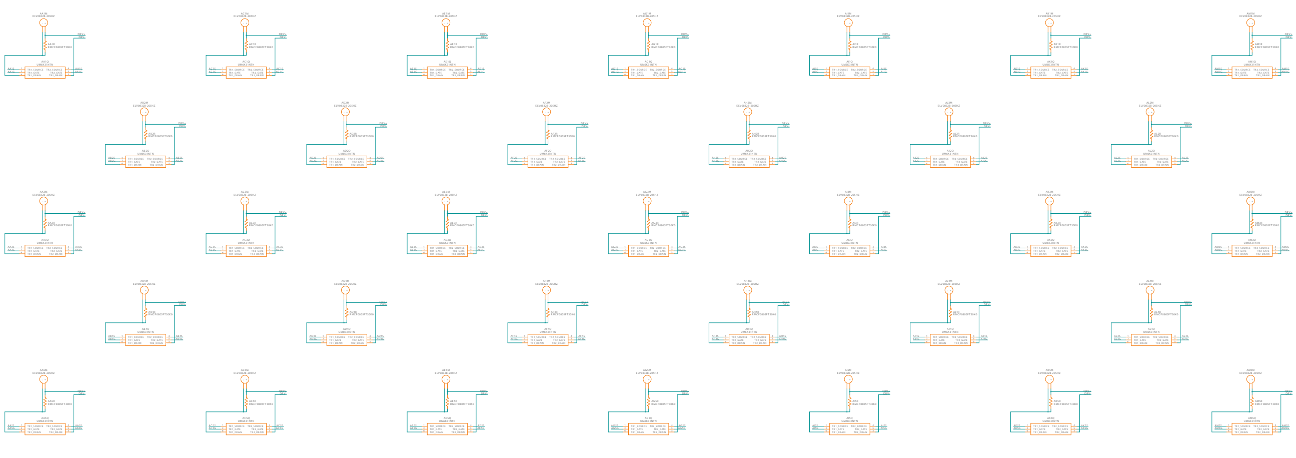

Fig. 29: The haptics board schematic “LRA Array” sheet.

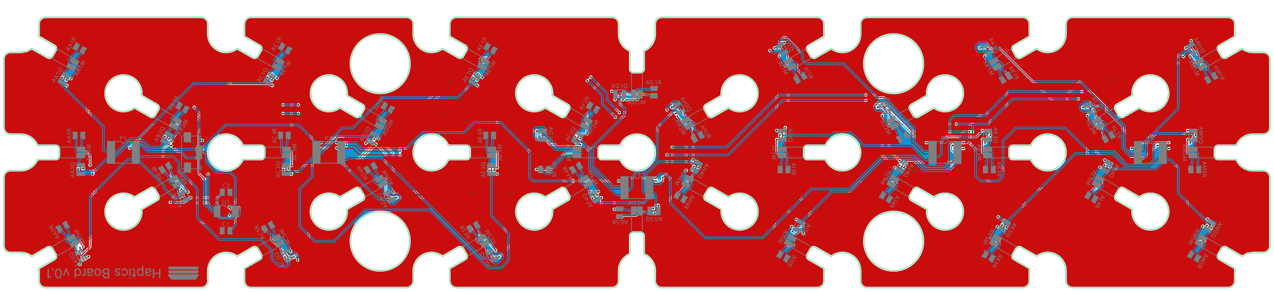

Fig. 30: The haptics board PCB front.

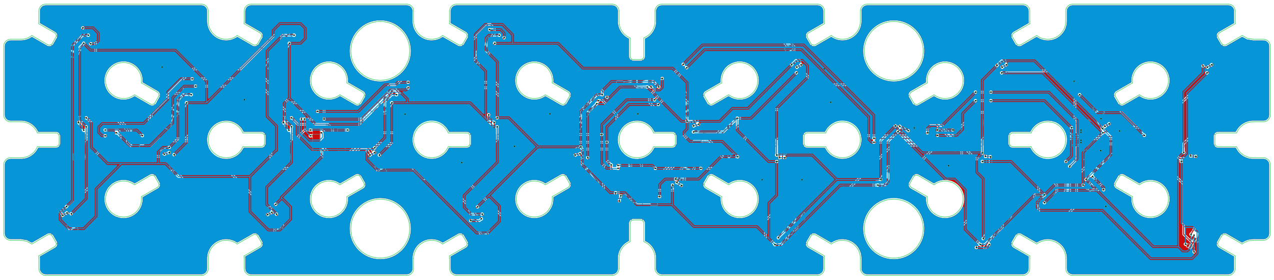

Fig. 31: The haptics board PCB back.

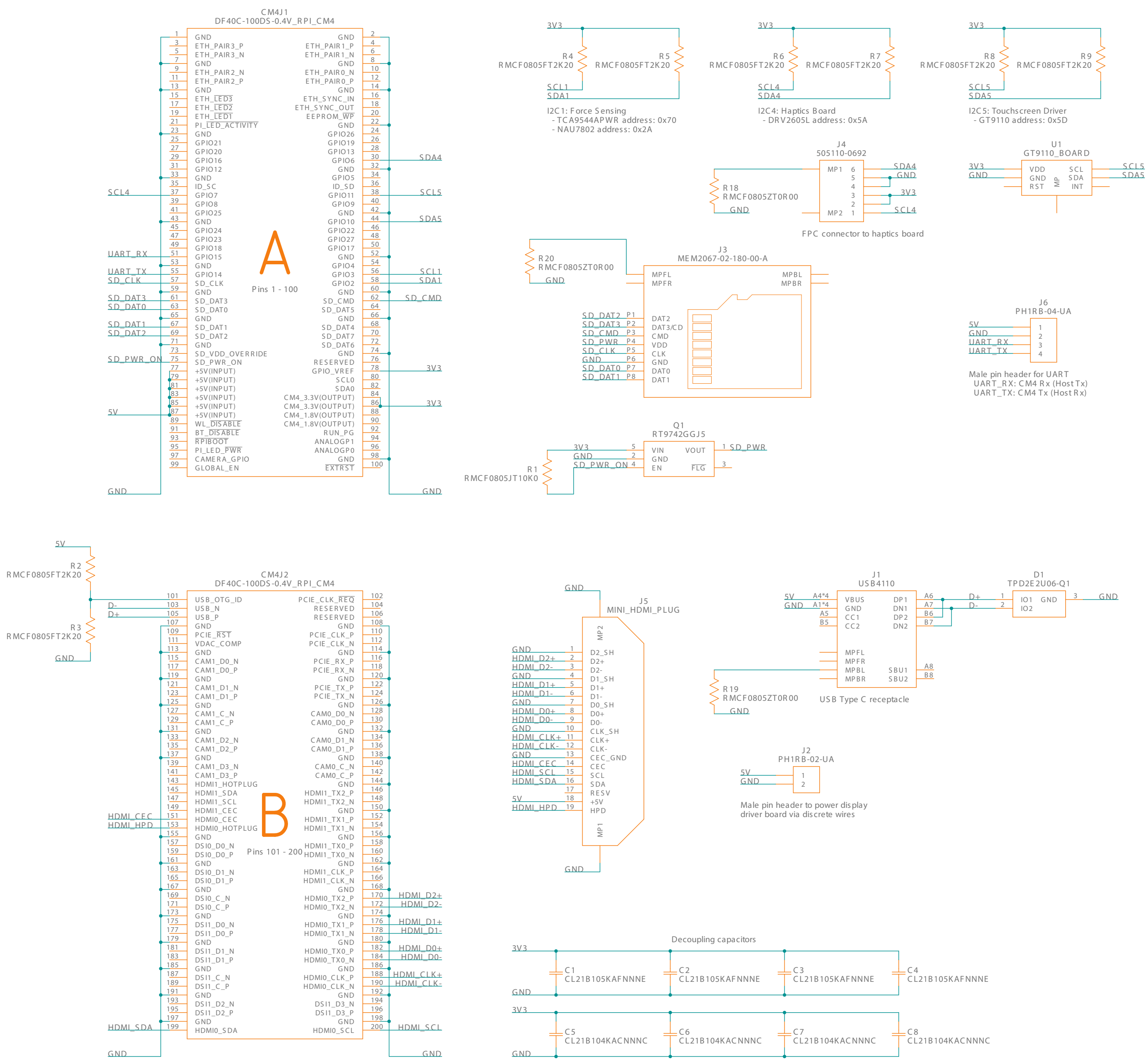

Fig. 32: The motherboard schematic “Processor” sheet.

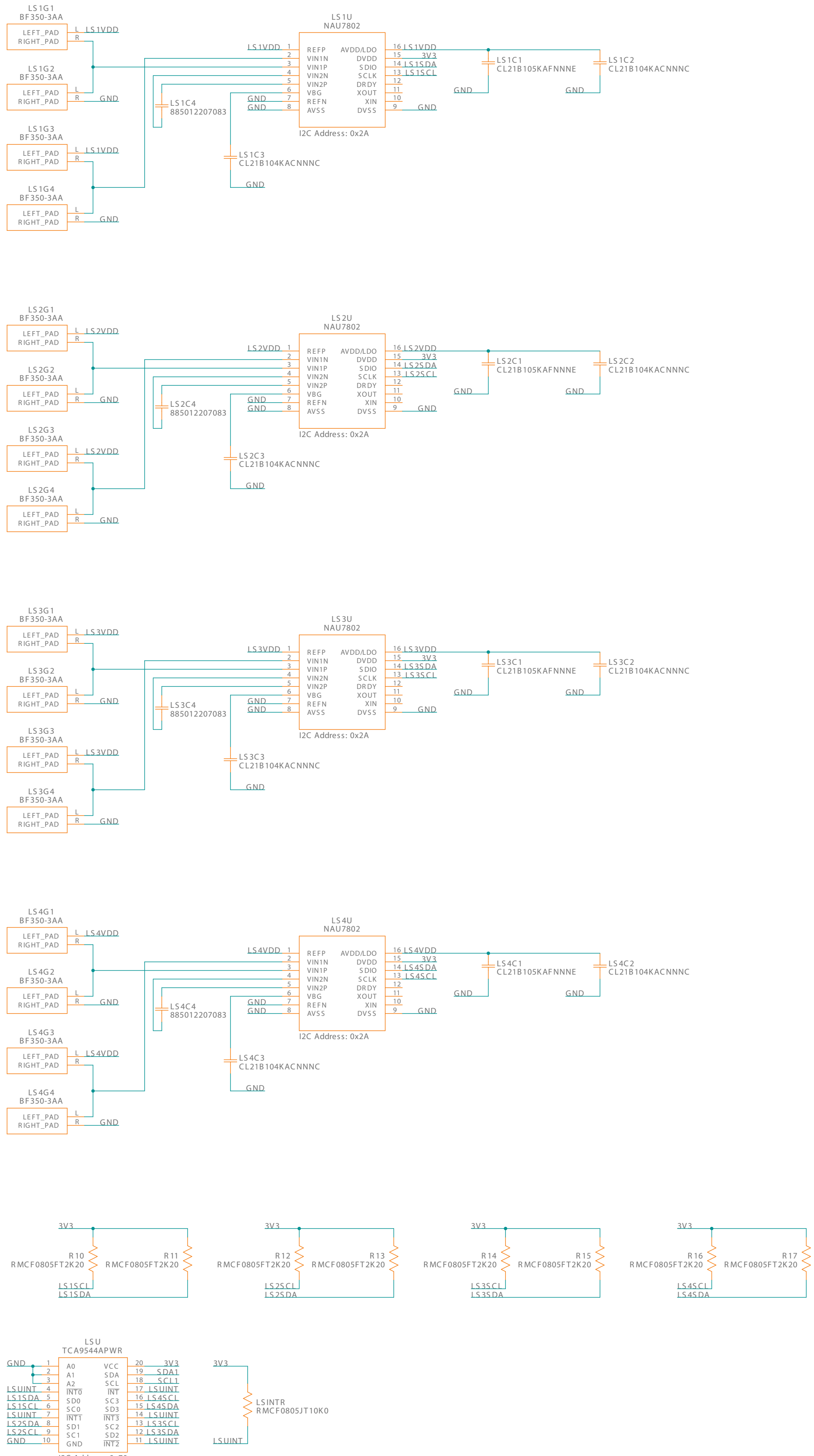

Fig. 33: The motherboard schematic “Load Surfaces” sheet.

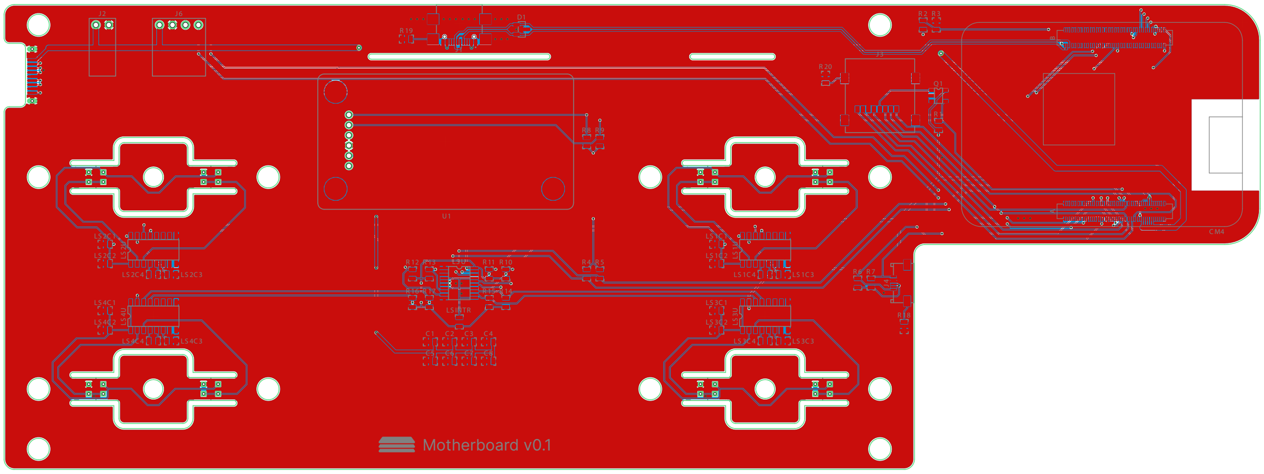

Fig. 34: The motherboard PCB front.

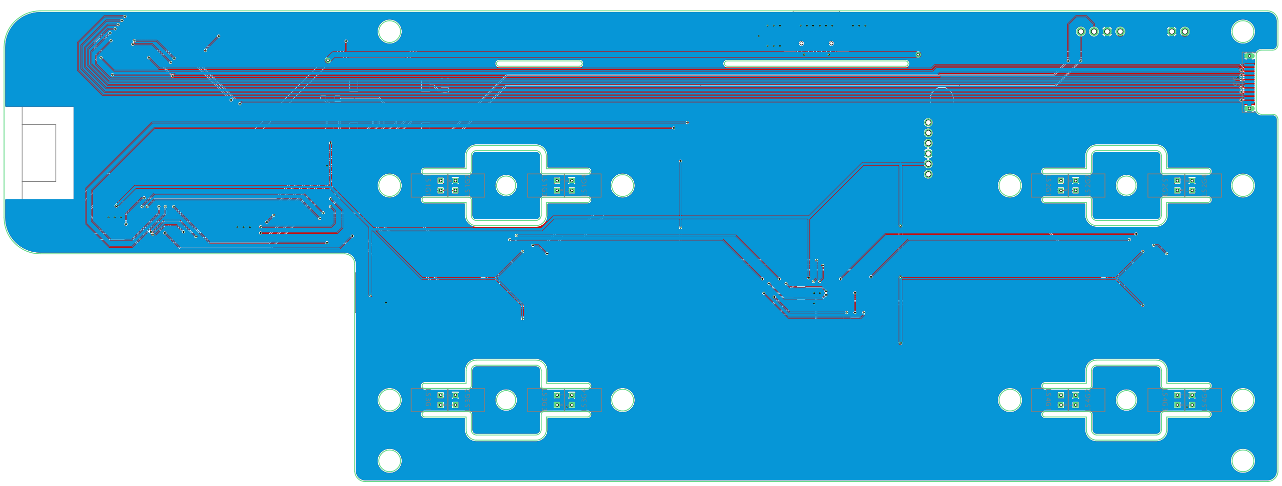

Fig. 35: The motherboard PCB back.

Fig. 36: The device bridge power board schematic.

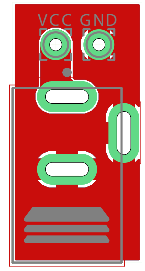

Fig. 37: The device bridge power board PCB front.

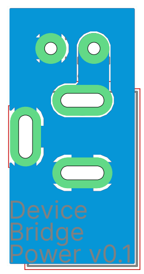

Fig. 38: The device bridge power board PCB back.

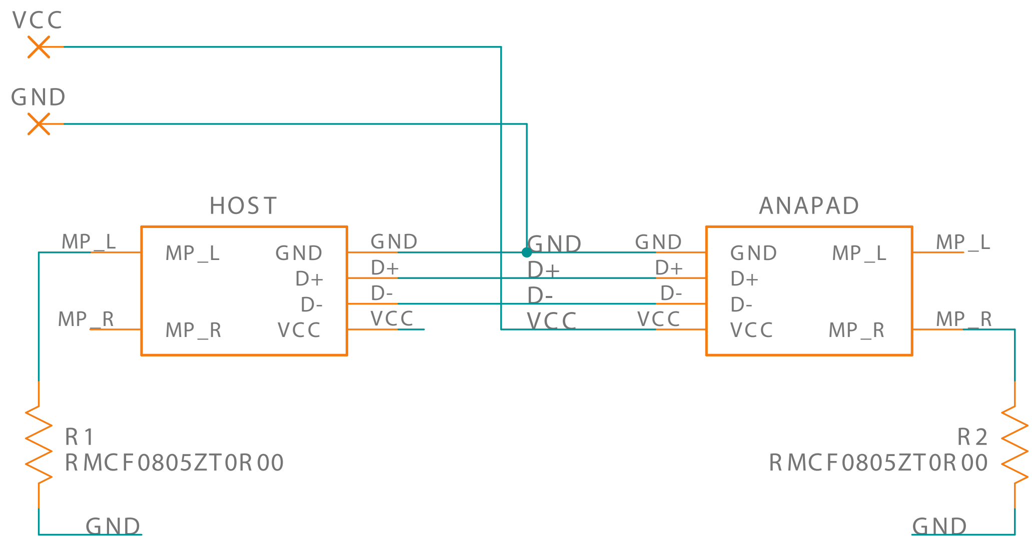

Fig. 39: The device bridge USB board schematic.

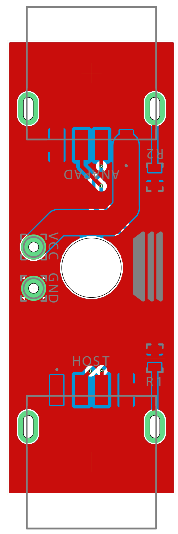

Fig. 40: The device bridge USB board PCB front.

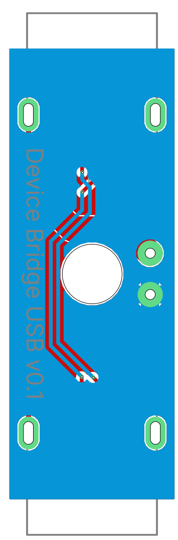

Fig. 41: The device bridge USB board PCB back.

Fig. 42: The workspace the Anapad Team used for the summer and fall semesters of 2022.

Fig. 43: Brady Hartog (left) and Jacob Peterson (right) (together the “Anapad Team”) standing in front of the their demo day display and each holding a Model A anapad.