The Bluetooth Audio Rejiggering Instrument (B.A.R.I.)

Authors: Adam Quinn, Xingran Du, Samuel Rainey: Electrical and Computer Engineering, Carnegie Mellon University

Abstract— **Most audio effects pedals are unable to interface with common Bluetooth speakers. In this paper, we present BARI, a 2-channel Bluetooth audio effects pedal aimed toward the casual/hobbyist musician market. BARI allows anyone to apply digital and true analog effects to up to two instruments or vocal channels and perform with any Bluetooth speaker.**

Index Terms— **audio effects, audio effects pedal, Bluetooth, Bluetooth speaker, distortion effect, overdrive effect, audio DSP, delay effect, equalization effect**

1 INTRODUCTION

Audio effects pedals are devices widely used by musicians to add "effects" such as distortion, delay, or equalization to the signals produced by their instruments. However, these pedals are typically costly and must be wired to bulky professional power amplifiers and speakers. Our product, the Bluetooth Audio Rejiggering Instrument, provides an inexpensive alternative for casual performers. BARI is a 2-channel Bluetooth audio effects pedal: it can apply a mix of digital and true analog effects that are competitive with desirable pedals. Unlike these pedals, it also broadcasts an output signal over Bluetooth, allowing high versatility as it can be used with cheap and extremely portable Bluetooth speakers.

In order for BARI to be an effective all-in-one solution for our target customers, it must be portable (maximum dimension < 15 cm, battery operated with a lifetime of at least 4 hours under standard operating conditions at room temperature), it must be inexpensive (< $100 fabrication cost at production pricing), and it must provide a set of minimum audio effects which include an analog overdrive effect and basic delay and EQ effects implemented digitally. It must also pair with all common Bluetooth speakers with a pairing range exceeding two meters. Further requirements are developed in the next section.

2 DESIGN REQUIREMENTS

2.1 Requirements and Justification

Design requirements for BARI are derived from our expectations about reasonable use of our device by casual musicians. The first four system requirements outline basic requirements for making the system usable by our intended customer, which are outlined in the introduction:

S.R. 1 - TEMPERATURE: The system shall meet all of the following requirements at room temperature (+27 C).

S.R. 2 - SYSTEM FORM FACTOR: To ensure portability, the system shall weigh less than 5 kilograms and its maximum dimension shall be less than 15 cm.

S.R. 3 - SYSTEM COST: The estimated production cost for the system at a volume of 10,000 units shall not exceed $100, where this estimate is calculated by the sum of: (a) Quoted PCB manufacturing cost for 10,000 units. (b) Component cost estimated at 10,000 unit volume pricing. (c) Estimated cost for the mechanical enclosure at 10,000 units.

S.R. 4 - BATTERY LIFETIME: The system shall be capable of operating on battery power for at least 4 hours of continuous operation at Standard Operating Profile.

–

The following three system requirements define the input to our system. These are based on our research regarding common signal and impedance characteristics for input devices (microphones, instruments) which may be used by our target customers:

S.R. 5 - INPUT CONNECTOR DEFINITION: The system shall have 2 audio input channels through hybrid connectors that will accept XLR (standard microphone) or 1/4" (standard electric guitar) plugs.

S.R. 6 - INPUT SIGNAL DEFINITION: The system should be capable of accepting any audio-frequency (20∼20 kHz) signal, with impedance from 100 to 40,000 ohms and magnitude from -60 dBV to +1.78 dBV, balanced or unbalanced. In particular, the system shall be capable of accepting the following common use cases: (a) "Quiet Mic": -59 dBV, ZOUT < 500 ohms, balanced; (b) "Hot Mic": -32 dBV, ZOUT < 500 ohms , balanced; and (c) Instrument: -59 dBV (passive) ∼ 1.78 dBV (active, line-level), ZOUT = 10 ∼ 40 kohms, unbalanced.

S.R. 7 - INPUT IMPEDANCE: The pre-amplifier's input impedance shall be: (a) Balanced, and (b) At least ten times the impedance of the highest-impedance allowed small-signal input (< -10 dBV) and at least two times the impedance of the highest-impedance allowed large-signal input (> 10 dBV).

–

The following three system requirements are flowed down requirements for the pre-amplifier block. In order for the system as a whole to exhibit high audio quality, the user's audio signals must experience low distortion during pre-amplification and arrive at the ADC interface with sufficient amplitude to achieve good SQNR.

S.R. 8 - PRE-AMPLIFIER OUTPUT: For each of the input the pre-amplifier shall produce an output voltage which is: Single-ended, referenced to the VSS supply of the system, and Tunable from -20 dBFS to -2 dBFS, where FS refers to the Full Scale of the microcontroller ADC (Approximately 3.3V)

S.R. 9 - PRE-AMPLIFIER GAIN FLATNESS: The gain of the pre-amplifier block shall differ by no more than 2 dB from its average value across the passband (20∼20 kHz)

S.R. 10 - PRE-AMPLIFIER DISTORTION: The pre-amplifier shall introduce total harmonic distortion not exceeding -60 dB(carrier) as approximated by the sum of the second and third harmonics of a test tone.

–

The defining feature of BARI is its Bluetooth capability. The following two system requirements define the range and connection protocol our Bluetooth module must support to be viable:

S.R. 11 - BLUETOOTH TRANSMISSION PROTOCOL: The system shall support the following Bluetooth specifications for audio transmission: (a) Bluetooth pairing to at least one Bluetooth audio output device, (b) Bluetooth version 3.0 or higher, (c) Low-Complexity Subband (SBC), Advanced Audio Coding (AAC), or other common codecs, capable of at least 250kbps, (d) Advanced Audio Distribution Profile (A2DP) Bluetooth profile.

S.R. 12 - BLUETOOTH TRANSMISSION RANGE: The average distance at which the system can maintain connection to a standard bluetooth speaker in an open air environment shall exceed 2 meters.

–

The following system requirements describe the digital effects that we must provide for a minimum viable product as well as metrics for the quality of each of these effects, as well as the overall latency of the digital processing. These figures are derived subjectively with advice from Sam Rainey regarding sound quality.

S.R. 13 - MINIMUM DIGITAL EFFECTS: The system shall be capable of applying any of the following digital effects (non-concurrently) to any of the two input channels independently, defined by the following requirements: (a) Equalization (EQ) and (b) Delay

S.R. 14 - EQUALIZATION QUALITY: For each equalization band in the system (at minimum, bass, middle, and treble), the system shall be able to adjust the magnitude of that band with a dynamic range of +/-15 dB, without affecting the amplitude in the non-adjusted bands by more than +/- 5 dB.

S.R. 15 - DELAY WET/DRY RATIO: The system shall be able to create a 0% wet delay output and a 100% wet delay output with 10 intermediate tuning steps.

S.R. 16 - DELAY TIME: The delay time shall be adjustable from 0 to 350 ms with 10 intermediate tuning steps.

S.R. 17 - PROCESSING LATENCY: The system shall have end-to-end latency of $<$ 100 ms from the system input to the Bluetooth send.

–

The final four system requirements determine both the form and the latency of our user interface, and they are defined to provide a responsive user experience:

S.R. 18 - USER INTERFACE RESPONSE LATENCY: The system shall finish responding to any user input (i.e. return feedback to the user) within 200 ms.

S.R. 19 - USER INTERFACE UPDATE LATENCY: When the user adjusts a parameter through the user interface, the system shall update its state (i.e. gain settings on analog circuitry and DSP parameters) within 1s.

S.R. 20 - USER INTERFACE INTERACTION TIME: The user shall be able to navigate to any command from the Home menu within 5s.

S.R. 21 - USER INTERFACE FEEDBACK MECHANISM: The system shall display a hierarchical menu in which the menu item that the user is currently interacting with is highlighted. The menu will contain: (a) All settings the user can adjust, and (b) The current system state.

–

The testing methodology for each of these requirements and the actual results achieved are presented in Section 6.

3 ARCHITECTURE OVERVIEW

The Bluetooth Audio Rejiggering Instrument accepts audio input from up to two XLR / 1/4” hybrid jacks. It mixes and applies effects to these audio signals based on a user directives given via an LCD + rotary encoder user interface. BARI then broadcasts the resultant signal over Bluetooth. BARI is battery-operated, and it can be recharged via a standard USB-C jack. The system is fully programmable via JTAG and a USB-to-UART converter.

BARI is integrated on a single printed circuit board which contains six distinct functional modules as seen in the block diagram (Fig. 1):

- The Pre-Amplifier Module
- The Analog Effect Module
- The Microcontroller Module
- The Bluetooth Module
- The User Interface Module
- The Power Module

The essential functions of each block and the interfaces between them are described below. By convention, an interface which is an output from module A to module B is listed under module A.

The Pre-Amplifier Module (2x) accepts balanced or unbalanced audio input signals (S.R. 6) and applies variable pre-ADC gain which is adjustable via an I2C-controlled digital potentiometer.

Interfaces:

- Analog audio output to Analog Effect Module or Microcontroller Module

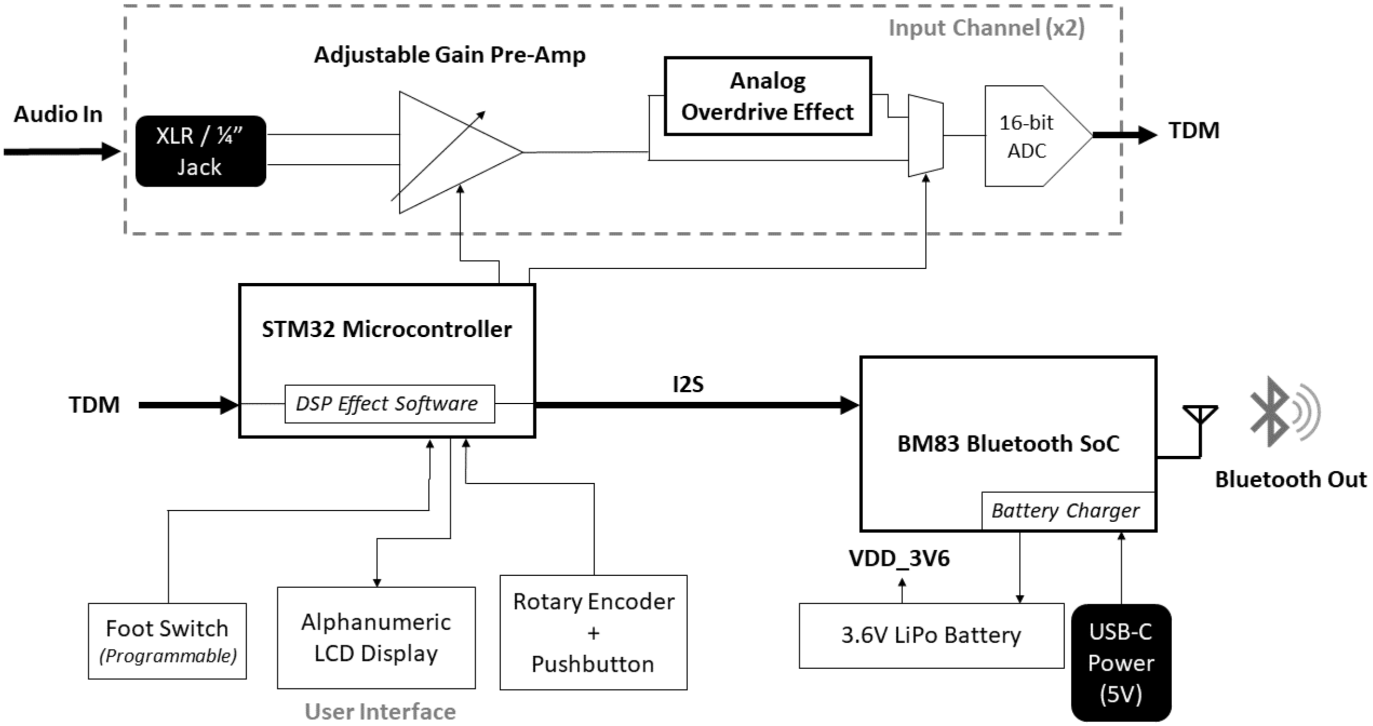


Figure 1: Bluetooth Audio Rejiggering Instrument (BARI) Block Diagram

The Analog Effect Module (2x) applies a variable amount of analog distortion to the Pre-Amplifier Module's output. An analog multiplexer controls whether the output from the Pre-Amplifier Module is passed through the Analog Effect Module, or whether it is directly passed to the Microcontroller Module without distortion.

Interfaces:

- Analog audio output to Microcontroller Module

The Microcontroller Module contains the core STM32 microcontroller which controls all other modules via SPI, I2C, and UART as well as applying digital audio effects. The module also contains the 24-bit external ADC which digitizes output from the previous two modules and passes it to the STM32 via time-domain-multiplexed SPI.

Interfaces:

- Time-Domain-Multiplexed SPI audio data from the external ADC to the microcontroller
- I2S audio output to the Bluetooth Module
- I2C control bus to the digital potentiometers in the Pre-Amplifier and Audio Effect Modules
- SPI control bus to the LCD in the User Interface Module
- UART control bus to the Bluetooth Module

The Bluetooth Module receives processed audio from the Microcontroller Module over Inter-Integrated Circuit Sound Bus (I2S) and broadcasts the signal as an output over Bluetooth.

Interfaces:

- Wireless audio output to an external Bluetooth speaker

The User Interface Module consists of an LCD screen and a rotary encoder with a push button, as well as a programmable foot switch. The LCD displays a menu structure with various options for the user while the rotary encoder allows the user to navigate the menus and make selections. The foot switch allows the user to quickly toggle on/off a selected effect.

Interfaces:

- Gray code output from the rotary encoder to the Microcontroller Module
- Discrete digital output from the foot switch and push button to the Microcontroller Module

The Power Module consists of the 3.6V rechargeable battery that supplies all other modules with power and the USB-C power port that allows the battery to be recharged.

Interfaces:

- N/A

4 DESIGN TRADE STUDIES

4.1 Implementation Plan (Make vs. Buy)

As described in the Architecture Overview, BARI is implemented on a custom printed circuit board. This means that the vast majority of the hardware is implemented as a custom design using standard components purchased from Digikey. The notable exception is the Analog Effect Module, which is referenced to a specific legacy pedal design as described below.

Our software is a mixture of custom modules (in particular our DSP and system control code) with STM32 and BM83 library code. Fig. 8 illustrates which software components are library vs. custom code.

4.2 Pre-Amplifier Module

4.2.1 Design Specification

The pre-amplifier module is the first block in the BARI signal path, and its performance is critical to ensuring system signal integrity. Its key specifications include the capability of providing a large, tunable gain (-60 dBV to +1.78 dBV, or a dynamic range of 61.78 dBV, S.R. 6) while maintaining gain flatness of less than 2 dB (S.R. 9) and introducing harmonic distortion not exceeding -60 dB (S.R. 10). These numbers were derived from comparable specifications for professional audio equipment, and they are intended to prove good signal integrity. Additionally, the pre-amplifier must have low Size, Weight, and Power (SWaP) as it will be implemented two times (once per channel).

4.2.2 Trades and Design Choice

Many different digitally tunable gain topologies were considered for the pre-amplifier block, including programmable gain amplifiers (PGAs), instrumentation amplifiers and audio amplifiers that are tunable via digital potentiometer, and multiplexed fixed gain blocks.

PGAs offer easy tuning, but they are not a good fit for the application: most of the inexpensive (<$3.00) PGAs we examined had only single-ended or low-impedance inputs. One promising candidate (LT1996) was only pin-programmable and thus not well suited for a digitally reprogrammable application.

Instrumentation Amplifiers offer excellent performance for very small input signals and balanced inputs (such as microphone signals), but they are less appropriate for large instrument-level signals. Many InAmps also have a minimum gain setting (5 V/V for the INA2332), which can cause clipping with our relatively low supply voltage.

Fixed gain blocks offer a wide dynamic range but very coarse tuning, which makes them at best only a partial solution to the problem.

We ultimately settled on a potentiometer-tunable audio-class amplifier, the MAX4061, which features balanced differential inputs, relatively low supply current (750 uA), tunable gain from 0∼40 dB, and excellent PSRR, CMRR, and THD+N characteristics. The one drawback of this choice was that the MAX4061 cannot meet our full required dynamic range. However, this was mitigated due to our choice of an ADC (the PCM1864) which includes over 30 dB of tunable analog gain. For the tuning potentiometer, we selected the MCP4451, which contains four potentiometers on a single chip that may be tuned easily using I2C.

For a full list of analog components that we considered, see smarturl.it/bari-analog-trades

4.2.3 Updates Since Design Review

On our final hardware revision, we use the MAX4062 as a preamplifier instead of the MAX4061. The two chips are nearly identical in functionality, but the MAX4062 has SOIC package, which is easier to solder correctly than the MAX4061's flat no-lead pacage.

4.3 Analog Effect Module

4.3.1 Design Specification

The primary specification for the analog effect module was to create a “desirable” analog distortion effect. For marketing and testability reasons, we decided to base our design on an existing analog effects pedal which could be simulated in SPICE to use as an objective comparison point.

4.3.2 Trades and Design Choice

The two primary effects we considered were analog delay and analog overdrive. We moved away from analog delay after learning that this effect is typically implemented with a “Bucket Brigade Device” (BBD) chip which is difficult to procure.

Our primary source for overdrive effects was the compilation of hobbyist schematics at Beavis Audio (*http://beavisaudio.com*). From the effects listed there, we downselected to the Colorsound Overdriver [1] effect due to its versatility, with the ability to produce a range of gain from light overdrive to heavy distortion and even fuzz. Other factors include its subjective “coolness” and the fact that it could be implemented with a relatively small number of components. We were also able to find detailed factory schematics for the original Colorsound Overdriver pedal, confirming this trade.

For a full list of analog components that we considered, see smarturl.it/bari-analog-trades

4.3.3 Updates Since Design Review

The Analog Effect Module is implemented in our final product and successfully applies distortion to the audio signal. However, because it was not part of our Minimum Viable Product, time constraints prevented us from fully and quantitatively verifying its functionality.

4.4 Microcontroller Module

4.4.1 Design specification

The microcontroller should have a supply voltage that is roughly in the range of common batteries and USB-C wall adapters, and better if it has low power consumption, so that the system can be portable and easy to charge. The Microcontroller Module should include an ADC of at least 16-bits to support high music signal quality. It should also support the LCD interface and common communication protocols like I2C, SPI, and I2S to interface with all other modules. An ARM core is preferred due to good programmability and our familiarity with it. It should have a low cost and have an affordable launchpad / discovery kit with peripherals similar to what we will actually have on our hardware to facilitate testing.

4.4.2 Trades and design choice

Table 1 shows the tradeoffs between 4 microcontroller options. The cost refers to the launchpad cost, which we will purchase for testing before our custom PCB arrives. The voltage for all 4 microcontrollers is 3.3V and thus the current (active/idle) indicates the power consumption level.

Our choice is the STM32F407VE microcontroller with external ADC PCM1864DBTR. The boards with built-in 16-bit ADCs are usually high performance and have high power cost as well as monetary cost, so we choose to use another external ADC instead. The STM32L496AG and STM32L4S5VIT6 are low power, and also have useful peripherals like the LCD or Bluetooth module on its launchpad, which is convenient for early-stage testing, but the price of the launchpad is too high comparing to the first option, and our power budget and schedule indicates that we would not require such low power.

4.5 Bluetooth Module

4.5.1 Design Specification

This subsystem is used for receiving the combination of the processed inputs and transmitting the output signal to a host Bluetooth audio device (S.R. 11(a)).

The transmission must support Bluetooth 3.0 or a more recent version of Bluetooth (S.R. 11(b)) for sufficient range, data rate, and reliability. The module must offer A2DP as the Bluetooth profile (S.R. 11(d)), which is the universal profile for audio information. The module must be compatible with either the SBC codec, which is supported by any output device that uses A2DP, or the AAC codec, which is the default codec for Apple devices (S.R. 11(c)).

This subsystem must be powered by our system voltage supply of 3.3V.

4.5.2 Trades and Design Choice

BlueCreation's BC127 is a Bluetooth module that features Bluetooth 4.0 with support for the low-latency aptX codec as well as the standard AAC and SBC codecs. However, there is poor documentation, hindering the ease of use. Each unit costs around $27.

Roving Network's RN-52 features Bluetooth 3.0 and supports the SBC codec. Like the BC127, there is little documentation. Each unit costs around $25.

Microchip's BM83 features Bluetooth 5.0 and supports the AAC and SBC codecs. There is ample usage documentation provided and there is an included feature for pairing two Bluetooth audio devices simultaneously called Wireless Concert Technology (WCT). Each unit costs around $11.

Refer to Table 2 for a chart comparing these modules.

The BM83 was selected for its excellent included documentation, low cost, and additional features including Bluetooth 5.0 and WCT.

4.6 User Interface Module

4.6.1 Design Specification

This subsystem includes inputs that a user can adjust to tune, toggle, or alter the system state as well outputs that clearly provide a user with information about the system.

The user interface (UI) module must meet ease of use requirements regarding latency, the display, and time to make adjustments. Any change to an effect parameter must be perceivable within 1 second of the change (S.R. 19). A user must be able to apply changes or toggle effects on any channel within 5 seconds (S.R. 20). Further, the UI must be no more than 5 menu layers deep. A typical menu layer interface is channel select, effect select, effect parameter select, and effect parameter adjustment. The display should be at least 30mm wide by 10mm tall and offer a resolution of at least 128x32 pixels for sufficient visibility. A back-light for the display is preferable but not essential.

The UI module must meet control resolution requirements in order to support fine-tuned control of effects parameters. A user must be able to apply different effects for each individual channel. Tuning of effects parameters must be possible as outlined in the system requirements. The user must have the ability to apply or disable each effect on a channel.

This subsystem must be powered by our system voltage supply of 3.3V.

In order to maximize tunability of effects for each channel, avoid cluttered buttons, and allow for flexible firmware updates, the UI module must include a screen display of some sort. Liquid-crystal display (LCD) screens are a good choice due to their availability, low price, and compatibility with microcontrollers.

A touchscreen thin-film-transistor (TFT) LCD would not provide ease of use when tuning effects parameters due to the accuracy expected of the user when adjusting parameters by small amounts. In addition, they are more expensive and consume more power than a standard LCD.

The best option for tuning resolution is a rotating dial so that a user has precise control. In addition, instead of a touchscreen interface, a button could be used to enter a

uC	Core	Cost	Current	ADC	DSP	Memory	Audio	Other feature
STM32F407VET6	M4 + FPU	\$20	40mA/0.3mA	12-bit (3)	Y	1M + 196K	I2S (2)	
STM32L496AG	M4 + FPU	\$70	7mA/2.8uA	12-bit (3)	Y	1M + 320K	SAI (2)	LCD on launchpad
STM32L4S5VIT6	M4 + FPU	\$54	13mA/2.8uA	12-bit (1)	Y	2M + 640K	SAI (3)	BT on launchpad
STM32H745XI	M7 + M4	\$87	(dual core)	16-bit (3)	Y	2M + 1M	SAI (4)	LCD on launchpad

Table 1: Microcontroller Trades

Module	Cost	Version	Codec(s)
BC127	\$27	Bluetooth 4.0	AAC SBC aptX
RN52	\$25	Bluetooth 3.0	SBC
BM83	\$11	Bluetooth 5.0	AAC SBC

Table 2: Bluetooth Module Trades

selection. An option that combines these two features is the rotary encoder with a pushbutton.

A system power switch and a programmable footswitch are UI components that are not specified in the MVP, but would be helpful for a user.

Our trade study focused on different LCD screens and rotary encoders with a pushbutton.

4.6.2 Trades and Design Choice

4.6.2.1 LCD

Newhaven Display's NHD-C12832A1Z-FSB-FBW-3V3 is a 128x32 pixel LCD that has a viewing area of 36mm by 12mm, runs on 3.0V (up to 3.3V), and uses the SPI protocol. The graphics color is black and the background color is blue, and it includes a back-light powered by 3.0V. Each unit costs around \$12.

Newhaven Display's NHD-C12864LZ-FSW-FBW-3V3 is a 128x64 pixel LCD that has a viewing area of 70mm by 40mm, runs on 3.0V (up to 3.3V), and uses an 8-bit parallel interface, supporting both 6800 and 8080 modes. The graphics color is black and the background color is white, and it includes a back-light powered by 3.0V. Each unit costs around \$16.

Newhaven Display's NHD-C12864WC-FSW-FBW-3V3 is a 128x64 pixel LCD that has a viewing area of 58mm by 28.8mm, runs on 3.3V, and uses SPI or an 8-bit parallel interface, supporting both 6800 and 8080 modes. The graphics color is black and the background color is white, and it includes a back-light powered by 3.3V. Each unit costs around \$17. An option with screw tabs is available for the same price.

Refer to Table 3 for a chart comparing these modules.

The NHD-C12864WC-FSW-FBW-3V3 was selected. The medium-size screen with good pixel resolution will keep the form factor down while increasing pixel density. The typical operation of 3.3V and up to 3.6V provides consistency with our other components. In addition, the screw tabs provide more options for the assembly of the final product.

4.6.2.2 Rotary Encoder with a Pushbutton

Bourns' PEC11-4215F-S24 is a rotary encoder with a pushbutton that has a 24-pulse encoder and is designed for audio applications. It includes a knob cap and each unit costs around \$5.

Bourns' PEC11R-4015F-S0018 is a rotary encoder with a pushbutton that has an 18-pulse encoder and is designed for audio applications. Each unit costs around \$2.

Bourns' PEC12R-3220F-S0024 is a rotary encoder with a pushbutton that has a 24-pulse encoder and is designed for audio applications. Each unit costs around \$1.

The PEC12R-3220F-S0024 was selected due to its low cost.

4.7 Power Module

4.7.1 Design specification

The power module should use commercial battery, be rechargeable, and support alternate input through USB-C wall adapter which is common for phone chargers. It should supply power to the whole system with a lifetime of at least 4 hours. With the microcontroller active current $I_{uP} = 40mA$ and the rest of the system below this number, we have $I_{total} = 80mA$, and thus

$$Capacity_{battery} \geq I_{total} \cdot 4h = 320mAh \qquad (1)$$

4.7.2 Trades and design choice

Lithium Polymer batteries are common for cellphones and are thus easily available. For microcontrollers, the common supply voltage is 3.3V. We looked into Lipo batterie of different capacities and found that a 1500mAh battery would provide sufficient slack room for the lifetime requirement, while having minimum marginal cost and reasonable dimensions. The Lipo battery uses a JST header, so we choose a B2B-PH-K-S(LF)(SN) JST male header, and a USB4125-GF-A USB-C jack as panel mount components on our board. The BM83 contains an integrated battery charger which can be used to recharge the battery from USB-C jack.

4.7.3 Updates Since Design Review

The battery recharging system using the BM83 is fully implemented in hardware. However, because battery recharging is not a part of our Minimum Viable Product,

Module	Cost	Viewing Area	Pixels	Color (Graphics, Background)	Backlight
NHD-C12832A1Z-FSB-FBW-3V3	$12	36mm x 12mm	128x32	Black, Blue	3.0V
NHD-C12864LZ-FSW-FBW-3V3	$16	70mm x 40mm	128x64	Black, White	3.3V
NHD-C12864WC-FSW-FBW-3V3	$17	58mm x 28.8mm	128x64	Black, White	3.6V

Table 3: LCD Trades

Signal	Direction	Description
SCL SDA	INPUT I2C	Digipot control bus

Table 4: Pre-Amplifier Interface

Signal	Direction	Description
EFFECT_SEL <3:0>	INPUT GPIO	Enable Analog Effect
SCL SDA	INPUT I2C	Digipot control bus

Table 5: Analog Effect Interface

Signal	Direction	Description
ADC_BCK ADC_LRCK ADC_DOUT	I/O SPI w/ TDM	commands and data
ADC_IRQ	OUTPUT Interrupt	interrupt output
SCL SDA	INPUT I2C	control (shared bus)
LED	OUTPUT LED	programmable LED

Table 6: ADC Interface

time constraints prevented us from verifying the software recharging algorithm.

5 SYSTEM DESCRIPTION

5.1 Pre-Amplifier Module

The Pre-Amplifier Module schematic is shown in Fig. 2. As shown, audio input signals are accepted through a hybrid XLR / 1/4" jack. (The hot Tip and cold Ring wires are shorted to the hot 2 and cold 3 wires respectively to allow either XLR or 1/4" signals to be passed to the same input path.) The signal is then capacitively coupled to the MAX4062 audio amplifier, which converts it to single-ended (if necessary) and passes the output to the Audio Effect Module and ADC. A solder jumper is provided to optionally short the cable shielding to ground if this will provide better performance. The wires labeled PA_POT0W (Pre-Amplifier Potentiometer, Channel 0, Wiper) and PA_POT0A (Pre-Amplifier Potentiometer, Channel 0, Terminal A) connect to the MAX4451 digital potentiometer.

5.2 Analog Effect Module

The Analog Effect Module schematic is show in Fig. 3. Like the original Colorsound Overdriver pedal, our overdrive effect consists of three stages. The first stage drives the signal magnitude into the saturation region of the two BJTs, producing soft clipping and harmonic distortion (colloquially known as "Fuzz Face"). The second stage is a tone stack, which controls the relative amplitude of the Bass and Treble bands. The third stage is purely an output buffer that sets the gain of the entire module. As with the pre-amplifier, the wires with labels in dashed gray boxes are potentiometer terminals.

5.3 Microcontroller

5.3.1 Interface

The microcontroller interfaces with all other modules as specified in other sections.

Our external ADC interfaces with the microcontroller as specified in Table 6. The ADC is controlled through an I2C bus shared with the Pre-Amp module and Analog Effect module, and the data outputs through an SPI bus which is Time-division Multiplexed (TDM) across the 2 input channels.

5.3.2 Control Software

The microcontroller processes the audio input streams and outputs a single I2S stream to the BM83 Bluetooth module. It also takes user inputs and controls the parameters of other modules. Fig. 8 shows the workflow of our microcontroller. In particular, the `Main Routine` manages the audio data flow, while the `UI Routine` responds to user actions by outputting control signals to other modules, while having minimal effects on the latency of the `Main Routine`.

5.3.2.1 Data Flow

The microcontroller receives the ADC output through a SPI bus with an additional Word Select (WS) line, which indicates the start of each time-division multiplexed frame containing 1 sample from each enabled input. The DSP algorithms will process the audio signal from the input buffer, and then store the resulting signal into output buffer. Then the processed signal is sent through I2S bus to the BM83 Bluetooth module.

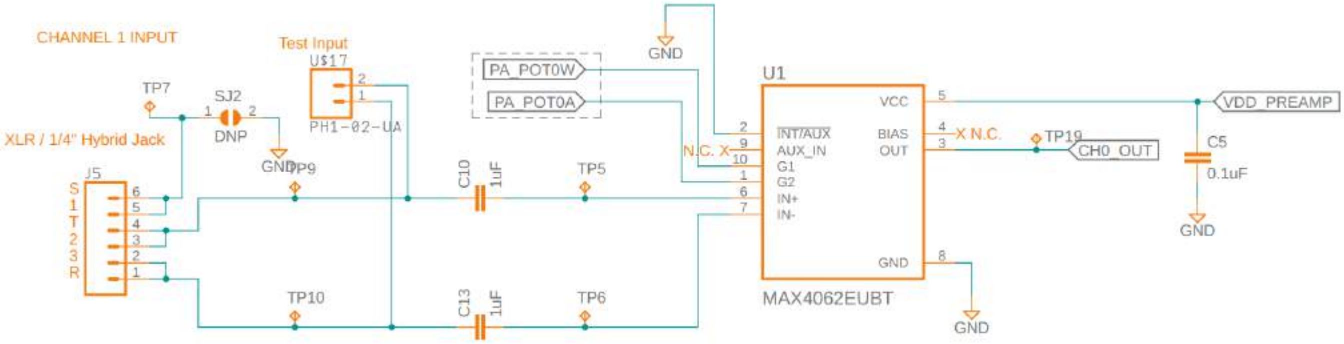


Figure 2: Pre-Amplifier Schematic

Both the input and output interfaces use Direct Memory Access (DMA) in order to free the processor from heavy I/O and ensure low latency.

5.3.2.2 Control Signal

The control events are handled in a polling routine, which system state changes triggered by user action. The user interacts with the rotary encoder or the foot switch, and the GPIO signal will inform the UI module to update the display parameters (which are driven to the LCD display in background by DMA). The UI module also parses the user input into actions, and the control module will base on these actions to output control signals to the Pre-Amp module (via GPIO and I2C), the Analog Effect module (via GPIO and I2C), and the Bluetooth module (via UART). The user inputs can also set the internal DSP parameters which takes effect immediately on the next processed block.

5.3.3 Digital Signal Processing

5.3.3.1 Implementation

The digital effects are implemented using a double-buffering scheme for both the input and output. This allows for block processing to reduce computational strain, still while inducing minimal latency. For BARI's implementation, each buffer in the double-buffer has 32 samples, and the ADC samples 24-bit data at a rate of 48kHz so 1.6 ms of latency is induced by block processing. The microcontroller has 192KB of SRAM, which is used for storing wet and dry inputs, outputs, computations, and control parameters.

5.3.3.2 Equalization

Equalization (EQ) is used to shape the frequency response of an input. The 3-band equalization effect is implemented using a low-shelf filter with a cut-off frequency of 200Hz with $Q = \sqrt{2}$, a mid-peak filter centered at 1kHz with $Q = 1.5$, and a high-shelf filter with a cut-off frequency of 5kHz with $Q = \sqrt{2}$. Using shelving and peaking filters allow for boosting or cutting across different frequency bands, enabling a user to select an increase in gain by setting a band to a setting of 6 to 10, a decrease in gain by setting a band to a setting of 1 to 4, or for no gain to be adjusted by setting a band to a setting of 5. A user will adjust the bass control to set the gain of the low-shelf filter, the middle control to set the gain of the mid-peak filter, and the treble control to set the gain of the high shelf filter.

During MATLAB prototyping of the shelving filters, an article and code on shelving filter design from DSPRelated.com was used as a reference [4]. The equations for coefficients were cross-referenced with equations from a Zölzer text on digital audio signal processing [14]. See Fig. 4 for a summary table of shelving filter equations [14].

Likewise, a different article from DSPRelated.com was referenced in prototyping the mid-peak filters [3], and the coefficient equations were cross-referenced with the same Zölzer text [14]. See Fig. 5 for a summary table of peaking filter equations [14].

EQ was implementing using a Direct-Form I implementation. See Fig. 6 for details [12].

5.3.3.3 Delay

Delay is used to apply an artificial echo to a signal, that is superimposing time-shifted and attenuated copies of a signal to an input to produce its output. The wet delay signal is implemented by delaying the sum of a feedback loop of the wet signal itself with a gain of less than 1 and the input signal. A gain of less than 1 is essential to provide a stable system and to produce a fading effect associated with natural echoes. The amount of delay is set by the user, up to 475 ms (S.R. 16). The output signal of the delay effect is determined by the wet/dry ratio set by the user, which tunes the gain of the wet and dry signals (S.R. 15). See Fig. 7 for a block diagram [6]. During MATLAB prototyping Analog Devices' tutorial on implementing delay was a particularly helpful resource [5].

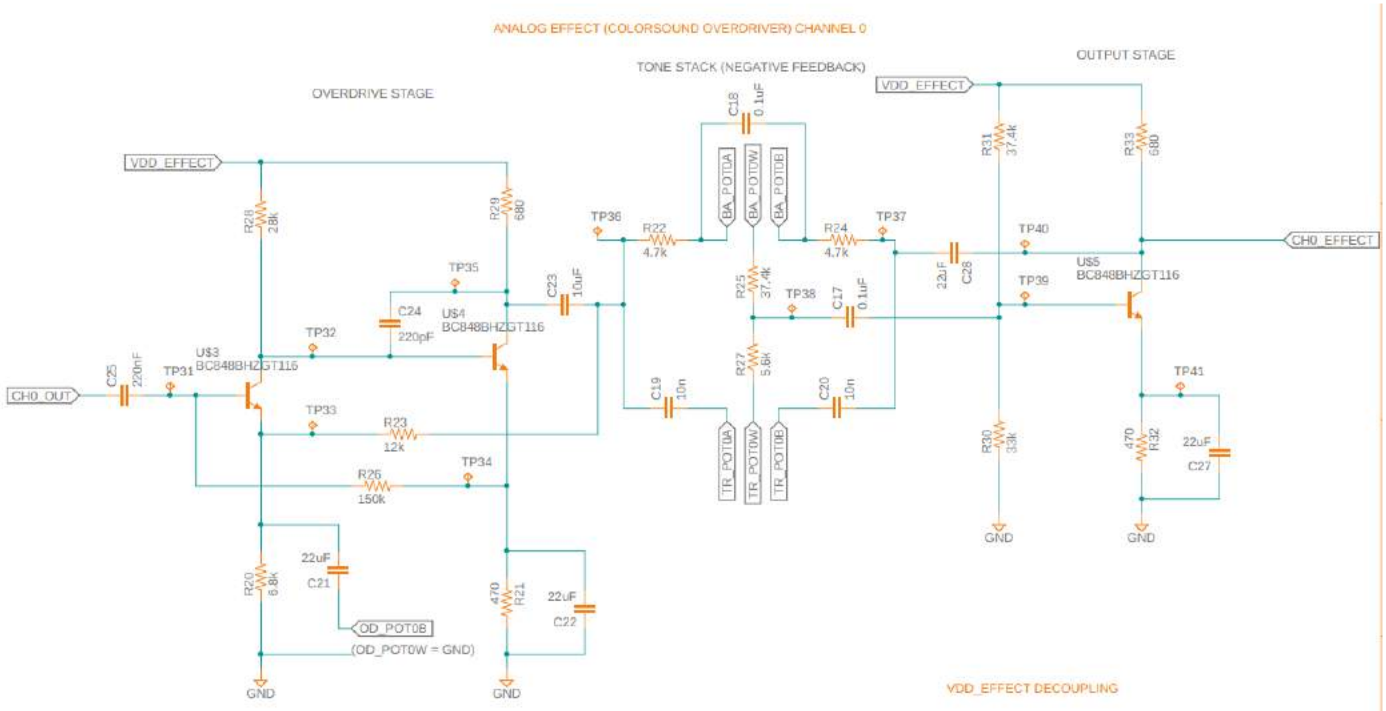


Figure 3: Analog Effect Schematic

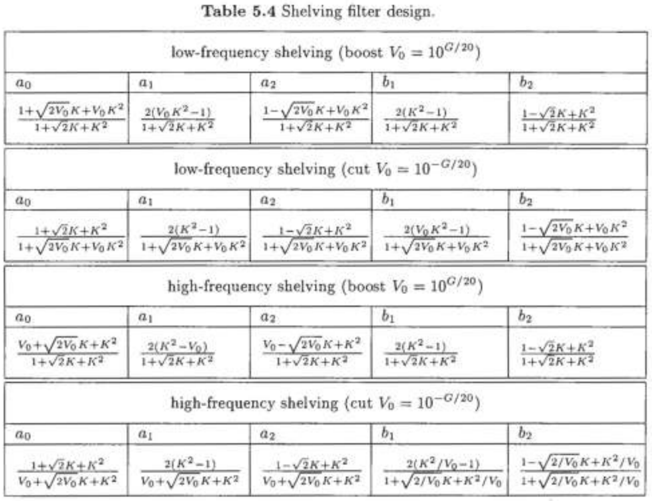


Table 5.4 Shelving filter design.

low-frequency shelving (boost $V_0 = 10^{G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{1+\sqrt{2V_0}K+V_0K^2}{1+\sqrt{2}K+K^2}$	$\frac{2(V_0K^2-1)}{1+\sqrt{2}K+K^2}$	$\frac{1-\sqrt{2V_0}K+V_0K^2}{1+\sqrt{2}K+K^2}$	$\frac{2(K^2-1)}{1+\sqrt{2}K+K^2}$	$\frac{1-\sqrt{2}K+K^2}{1+\sqrt{2}K+K^2}$

low-frequency shelving (cut $V_0 = 10^{-G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{1+\sqrt{2}K+K^2}{1+\sqrt{2V_0}K+V_0K^2}$	$\frac{2(K^2-1)}{1+\sqrt{2V_0}K+V_0K^2}$	$\frac{1-\sqrt{2}K+K^2}{1+\sqrt{2V_0}K+V_0K^2}$	$\frac{2(V_0K^2-1)}{1+\sqrt{2V_0}K+V_0K^2}$	$\frac{1-\sqrt{2V_0}K+V_0K^2}{1+\sqrt{2V_0}K+V_0K^2}$

high-frequency shelving (boost $V_0 = 10^{G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{V_0+\sqrt{2V_0}K+K^2}{1+\sqrt{2}K+K^2}$	$\frac{2(K^2-V_0)}{1+\sqrt{2}K+K^2}$	$\frac{V_0-\sqrt{2V_0}K+K^2}{1+\sqrt{2}K+K^2}$	$\frac{2(K^2-1)}{1+\sqrt{2}K+K^2}$	$\frac{1-\sqrt{2}K+K^2}{1+\sqrt{2}K+K^2}$

high-frequency shelving (cut $V_0 = 10^{-G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{1+\sqrt{2}K+K^2}{V_0+\sqrt{2V_0}K+K^2}$	$\frac{2(K^2-1)}{V_0+\sqrt{2V_0}K+K^2}$	$\frac{1-\sqrt{2}K+K^2}{V_0+\sqrt{2V_0}K+K^2}$	$\frac{2(K^2/V_0-1)}{1+\sqrt{2/V_0}K+K^2/V_0}$	$\frac{1-\sqrt{2/V_0}K+K^2/V_0}{1+\sqrt{2/V_0}K+K^2/V_0}$

Figure 4: Shelving Filter Equations

5.4 Bluetooth Module

5.4.1 Interface

Our Bluetooth module BM83 interfaces with the microcontroller as specified in Table 7. The Bluetooth receives audio input from the microcontroller via an I2S bus, and receives reset or wakeup signal from the microcontroller GPIO upon powering up.

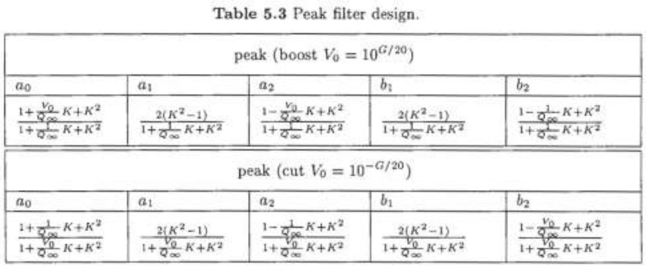


Table 5.3 Peak filter design.

peak (boost $V_0 = 10^{G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{1+\frac{V_0}{Q_\infty}K+K^2}{1+\frac{1}{Q_\infty}K+K^2}$	$\frac{2(K^2-1)}{1+\frac{1}{Q_\infty}K+K^2}$	$\frac{1-\frac{V_0}{Q_\infty}K+K^2}{1+\frac{1}{Q_\infty}K+K^2}$	$\frac{2(K^2-1)}{1+\frac{1}{Q_\infty}K+K^2}$	$\frac{1-\frac{1}{Q_\infty}K+K^2}{1+\frac{1}{Q_\infty}K+K^2}$

peak (cut $V_0 = 10^{-G/20}$)				
a_0	a_1	a_2	b_1	b_2
$\frac{1+\frac{1}{Q_\infty}K+K^2}{1+\frac{V_0}{Q_\infty}K+K^2}$	$\frac{2(K^2-1)}{1+\frac{V_0}{Q_\infty}K+K^2}$	$\frac{1-\frac{1}{Q_\infty}K+K^2}{1+\frac{V_0}{Q_\infty}K+K^2}$	$\frac{2(K^2-1)}{1+\frac{V_0}{Q_\infty}K+K^2}$	$\frac{1-\frac{V_0}{Q_\infty}K+K^2}{1+\frac{V_0}{Q_\infty}K+K^2}$

Figure 5: Peaking Filter Equations

5.4.2 Control Protocol

The BM83 receives commands and replies its status through the UART interface. The BM83 software package includes a SPKCommandSetTool [10] which is a GUI tool on PC. All the necessary operations to put BM83 into standby mode, discover Bluetooth devices nearby, and connect to a selected device could be done through this tool. Figure 9 shows some available commands in the SPKCommandSetTool we use for controlling the BM83.

5.5 User Interface Module

5.5.1 Microcontroller Interface

The UI module interfaces with the microcontroller as specified in Table 8.

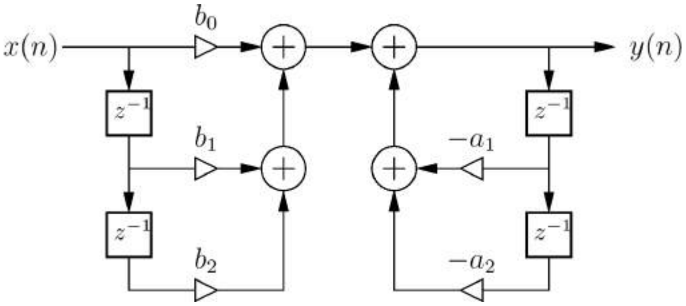


Figure 6: Direct-Form I Signal Flow Graph

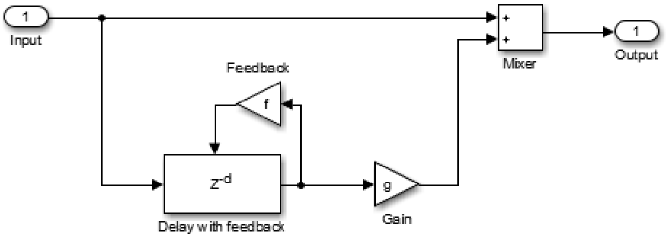


Figure 7: Delay Block Diagram

5.5.2 Wireframe

A menu layout wireframe is conceptualized in Fig. 10. The realized wireframe is included in Fig. 11 for reference.

5.5.3 LCD Interfacing

Communication with the LCD was facilitated through the SPI protocol, using the manufacturer's command interface to execute items including initializing the LCD upon boot-up and writing individual pixels to the display. A character font that converts alphanumeric characters and common symbols to 8x5 pixel arrays was implemented based on a font provided by Yuxar Consulting Corp. [13]. When any element of the UI state is updated, the entire menu screen is refreshed, row by row.

5.5.4 Settings Adjustment

A polling routine is used to receive input from a user from the rotary encoder, push button, and foot switch.

The foot switch is programmable from the Switch Assignment menu, set to one of the two channels, and to toggle either the Channel, Delay, EQ, or Overdrive Enable for that channel. Software debouncing is used for accurate input processing. When the foot switch is pressed from any menu, the assigned effect is toggle between on and off.

The rotary encoder and push button allow a user to navigate through menus. Menu items wrap around, so a user can reach the bottom item by rotating counter-clockwise from the top or the top item by rotating clockwise from the bottom. The push button has a different function based on the menu item. For items such as enable toggles and channel selects pushing the button toggles between the item options, such as On and Off or Channel and Channel 2. For items such as effect selects and parameter tuning pushing the button allows a user to then make a selection by turning the rotary encoder. In some cases, such as effect selects, these items wrap around circularly. In others, such as parameter tuning, a user cannot select a setting below the minimum or above the maximum programmed limit for the setting. A user must press the button again to change the function of the rotary encoder back to menu navigation. Certain menu items will bring you to another menu to make further adjustments when you press the button. For instance, the Go Back item takes a user to the top of the previous menu.

Signal	**Direction**	**Description**
BT_RFS BT_SCLK BT_DR	INPUT I2S	Digital audio input
BT_MFB	INPUT GPIO	BM83 wakeup
BT_RSTB	INPUT GPIO	reset (active low)
BT_MCWAKE	OUTPUT GPIO	microcontroller wakeup

Table 7: BM83 Interface

Signal	**Direction**	**Description**
LCD_SCK LCD_MOSI	IN/OUT SPI	Serial clock and data
LCD_CS1B	INPUT GPIO	Active low chip select
LCD_A0	INPUT GPIO	Register select
LCD_PS	INPUT	Parallel/serial select
LCD_RSTB	INPUT GPIO	Active low reset
RENC_A	OUTPUT GPIO	Encoder output channel A
RENC_C	OUTPUT	Encoder common output
RENC_B	OUTPUT GPIO	Encoder output channel B
BUTTON_T1	OUTPUT GPIO	Pushbutton output pin 1
BUTTON_T2	OUTPUT GPIO	Pushbutton output pin 2
FOOTSWITCH_T1	OUTPUT GPIO	Footswitch output pin 1
FOOTSWITCH_T2	OUTPUT GPIO	Footswitch output pin 2

Table 8: UI Interface

See Fig. 10 or Fig. 11 for menu layers and settings on each menu.

Table 8 shows global variables that are adjusted by the UI.

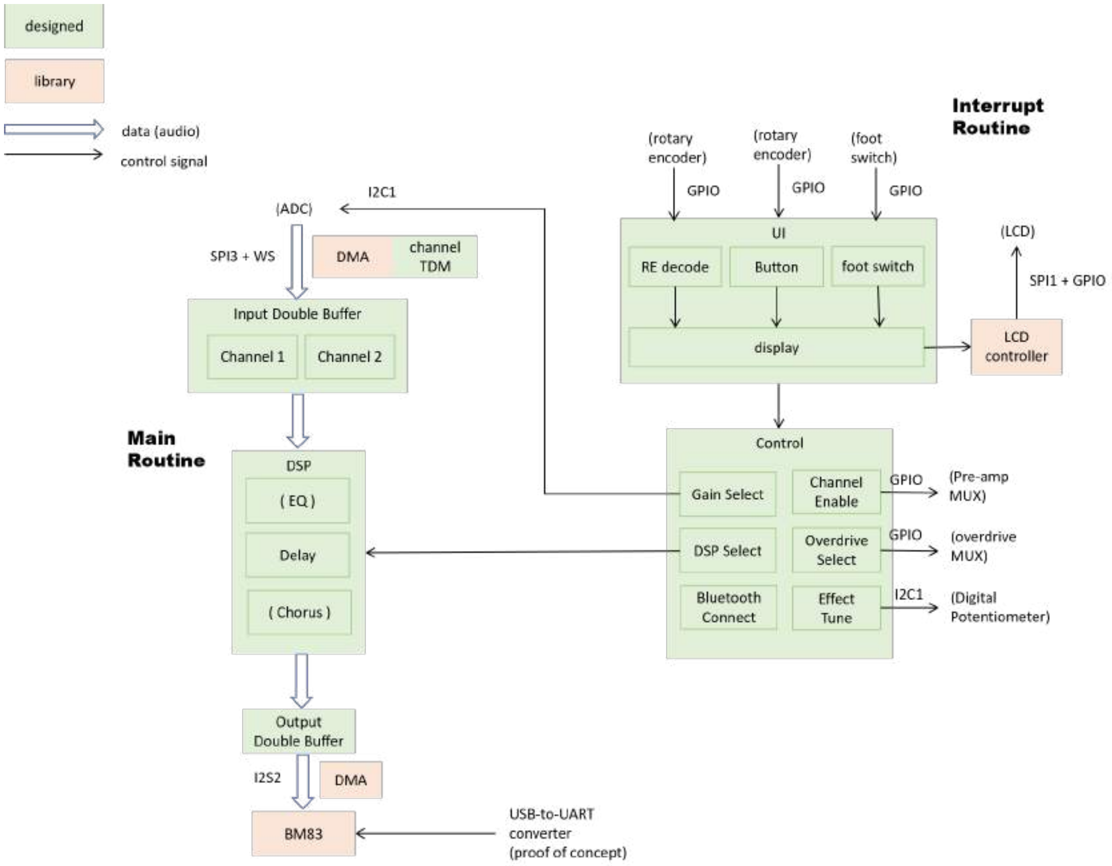
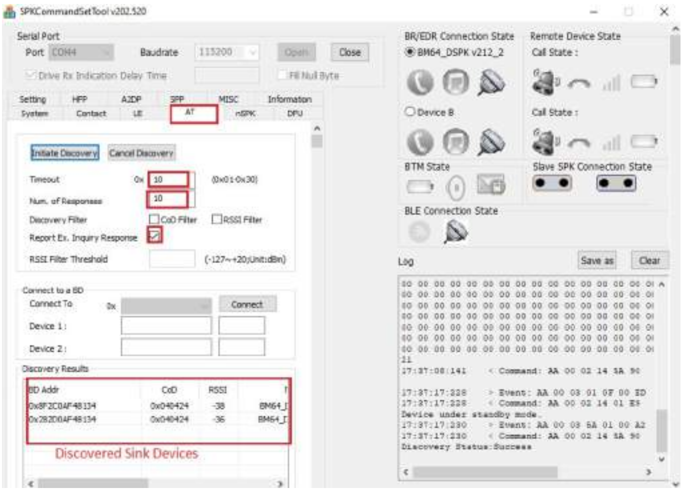


Figure 8: Software Block Diagram



Port: COM4
Baudrate: 115200
☑ Drive Rx Indication Delay Time
☐ Fill Null Byte
○ BM64_DSPK v212_2
Timeout 0x 10 (0x01-0x30)
Num. of Responses 10
Discovery Filter ☐ CoD Filter ☐ RSSI Filter
Report Ex. Inquiry Response ☑
RSSI Filter Threshold (-127~+20;Unit:dBm)
Connect To 0x
Device 1 :
Device 2 :

BD Addr	CoD	RSSI	
0x8F2C0AF48134	0x040424	-38	BM64_I
0x282D0AF48134	0x040424	-36	BM64_I

```
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 0
11
17:37:08:141    < Command: AA 00 02 14 5A 90

17:37:17:228    > Event: AA 00 03 01 0F 00 ED
17:37:17:228    < Command: AA 00 02 14 01 E9
Device under standby mode.
17:37:17:230    > Event: AA 00 03 5A 01 00 A2
17:37:17:230    < Command: AA 00 02 14 5A 90
Discovery Status:Success
```

Figure 9: BM83 Control Software

5.6 Power Module

The Power Module schematic is given in Fig. 12.

5.6.1 Battery

The main power source for BARI is a 3.6V LiPo battery, which provides DC power to all other subsystems. The sense resistors R3R7 allow the power consumed by each subsystem to be independently measured. Additionally, the PGOOD LED U$11 is illuminated if power to the system is switched on.

5.6.2 Charging

In principle, the 3.6V LiPo battery may be recharged through a 5V USBC charging cable. The USBC socket placed on the PCB is a poweronly socket which exposes only six pins. R1 and R2 are selected to comply with the USBC protocol and D1 provides electrostatic protection for the system. A solder jumper is provided to optionally short the shield of the USB cable to the ground of the system. Note that the battery is not connected directly to the charging port: charging current and voltage is mediated by a battery charging circuit that is part of the BM83. As mentioned above, verifying the software algorithm that manages recharging current remains as future work. Rechargeability is an additional feature outside the scope of our Minimum Viable Product.

6 TEST & VALIDATION

6.1 Results for S.R. 1 - Temperature

All of the below tests were performed indoors at nominal room temperature (+27 C). Thus the success of the tests

Parameter	Module	Type	Description
CH1_GAIN	Pre-Amp	unsigned char	Pre-amp gain from 1 to 10
CH1_EN	Microcontroller	unsigned char	Software enable that determines if channel signal is processed and sent to the output buffer
CH1_OD_EN	Analog Overdrive	unsigned char	Overdrive effect enable
CH1_OD_GAIN	Analog Overdrive	unsigned char	Overdrive effect gain from 1 to 10
CH1_OD_B	Analog Overdrive	unsigned char	Analog bass level from 1 to 10
CH1_OD_T	Analog Overdrive	unsigned char	Analog treble level from 1 to 10
CH1_DEL_EN	Delay	unsigned char	Delay effect enable
CH1_DEL_TIME	Delay	uint16_t	Delay time from 0 to 475ms i.e. time delay of first superimposed copy of the input signal
CH1_DEL_FB	Delay	unsigned char	Delay feedback level from 0 to 0.9. Determines decay rate of the delay feedback loop
CH1_DEL_WET	Delay	unsigned char	Delay wet percentage from 0 to 100% i.e. how much of the output signal is from the delayed copies of the input
CH1_EQ_EN	EQ	unsigned char	EQ effect enable
CH1_EQ_B	EQ	unsigned char	EQ bass level from 1 to 10
CH1_EQ_M	EQ	unsigned char	EQ middle level from 1 to 10
CH1_EQ_T	EQ	unsigned char	EQ treble level from 1 to 10

Table 9: UI global parameters for Channel 1. Note that Channel 2 also has copies of these parameters but are excluded for succinctness.

below serves to validate S.R. 1.

6.2 Results for S.R. 2 - System Form Factor

BARI, fully assembled, is 9.5cm tall from base to the tip of the rotary encoder knob, 10.4cm long across the front, and 7.9cm deep from the front to the back. See Fig. 13 for a diagram. BARI, fully assembled, is 0.24kg. All dimensions are less than 15cm and the weight is less than 5kg, validating S.R. 2.

6.3 Results for S.R. 3 - System Cost

To evaluate the hypothetical production cost for BARI at scale, we estimated the cost of the three items listed in S.R. 3 (PCB cost, component cost, and mechanical enclosure cost.) The total cost for these budget items came out to \$25.20 as shown in Table 10, substantially below our target of \$100.00. Other factors that are more difficult to estimate include labor costs, shipping, and regulatory compliance costs. These are not included in S.R. 3, but considering the large margin between our target and actual cost, these factors should not prove to be significant obstacle to the manufacturing of BARI.

The sources for the production volume costs in Table 10 are as follows:

- PCB costs are taken from an assembly quote from JLCPCB, our PCB supplier.
- Component costs are taken from a quote from Digikey, our main components supplier.
- Mechanical enclosure costs are calculated based on the mass of BARI's mechanical enclosure under the assumption that the final enclosure would be injection-molded at costs comparable to those described in [11].

6.4 Results for S.R. 4 - Battery Lifetime

S.R. 4 was verified by measuring the actual current draw of BARI under typical conditions and comparing it to the nominal capacity of our chosen battery. (See Table 11.) "Typical conditions" are defined as streaming audio from a single source with a nominal analog gain of +0 dB and broadcasting over Bluetooth. A 50% derating factor is applied primarily to account for non-idealities in the battery discharge curve.

The calculated lifetime of 8.92 hours exceeds the specified minimum lifetime of 4 hours.

6.5 Results for S.R. 5 - Input Connector Definition

Two Neutrik NCJ9FI-S Combo XLR 1/4" connectors are used as inputs to BARI, satisfying S.R. 5 by design.

6.6 Results for S.R. 6 - Input Signal Definition

Refer to S.R. 7 and S.R. 8. The high input impedance of the preamplifier specified in S.R. 7 guarantees no more than -2.8 dB attenuation for large-signal sources, and no more than -0.04 dB attenuation for small-signal sources. As calculated in S.R. 8, the smallest acceptable signal per

Budget Item	**Cost (Single Unit @ Vol. 1)**	**Cost (10,000 Units)**	**Cost (Single Unit @ Vol. 10,000)**
Rev 2 PCB Manufacture and Assembly	$9.14	$4,444	$0.44
Rev 2 Components (Digikey)	$38.45	$243,609	$24.37
Rev 2 Mechanical Enclosure	$67.20	$3,852	$0.39
TOTAL	$114.79	$251,905	$25.20

Table 10: BARI Manufacturing Cost at Scale

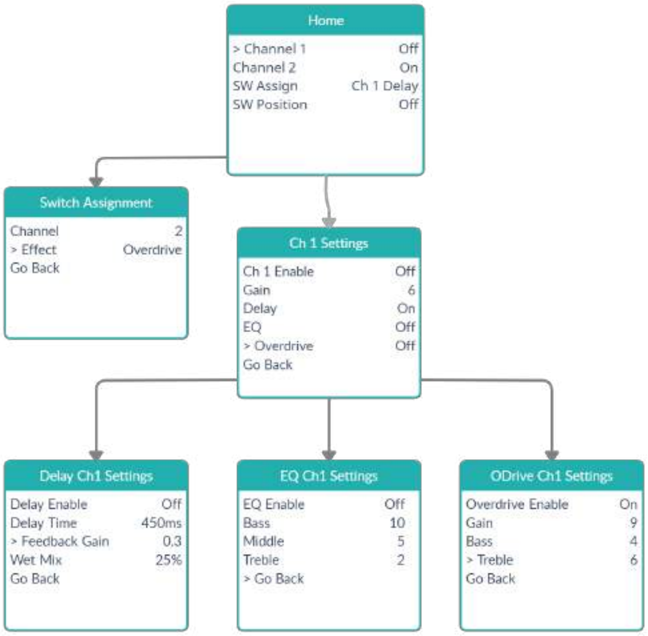


Figure 10: Wireframe Conceptualization

BARI Typical Current Consumption	84.0 mA
Nominal Capacity of AKZYTUE 3.7V LiPo Battery	1500 mAh
Derating Factor	0.5
Battery Lifetime	8.92 hours

Table 11: BARI Power Consumption and Battery Life

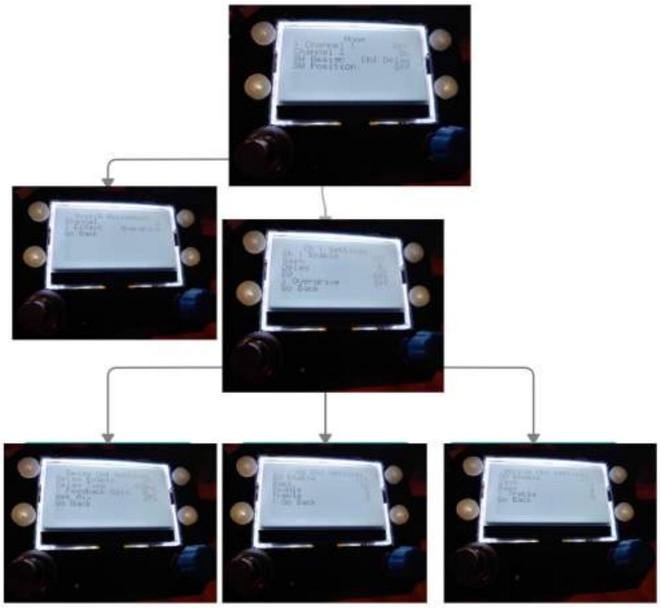


Figure 11: Wireframe Realized

MAX4062 Input Impedance (ohms)	100k +/- 1k
Coupling Capacitance (farads)	1 uF +/- 0.02 uF
Coupling Capacitor Impedance at 20 Hz (ohms)	7.96k +/- 159 ohms
Total Input Impedance at 20 Hz	108k +/- 1.1k

Table 12: Pre-Amplifier Input Impedance Calculations

S.R. 6 can be amplified to an acceptable amplitude. Thus all signals in this definition are accepted by the system.

6.7 Results for S.R. 7 - Input Impedance

By referring to the impedance specifications in S.R. 6, we find that the minimum required input impedance is the *greater* of $80k\Omega$ (2x the highest impedance of a large-signal source, $40k\Omega$) and $5k\Omega$ (10x the highest impedance of a small-signal source, $500k\Omega$), which is $80k\Omega$.

The input impedance of the two inputs of the MAX4062 are $100k\Omega$, meeting this requirement. The inputs are also balanced, matching to within 1%.

Note that BARI's inputs are AC-coupled to the inputs of the preamplifier. However, the coupling capacitors are intentionally chosen to have large values such that their mismatch does not substantially affect overall matching, as shown in Table 12. This table conservatively measures input matching at the lowest frequencies of BARI's operation. Matching at higher frequencies is better due to a smaller contribution from coupling capacitors.

6.8 Results for S.R. 8 - Pre-Amplifier Output

In the final BARI design, the gain of the pre-amplifier is combined with the internal gain of the ADC to create a tunable cascade with values given in Table 13. In order

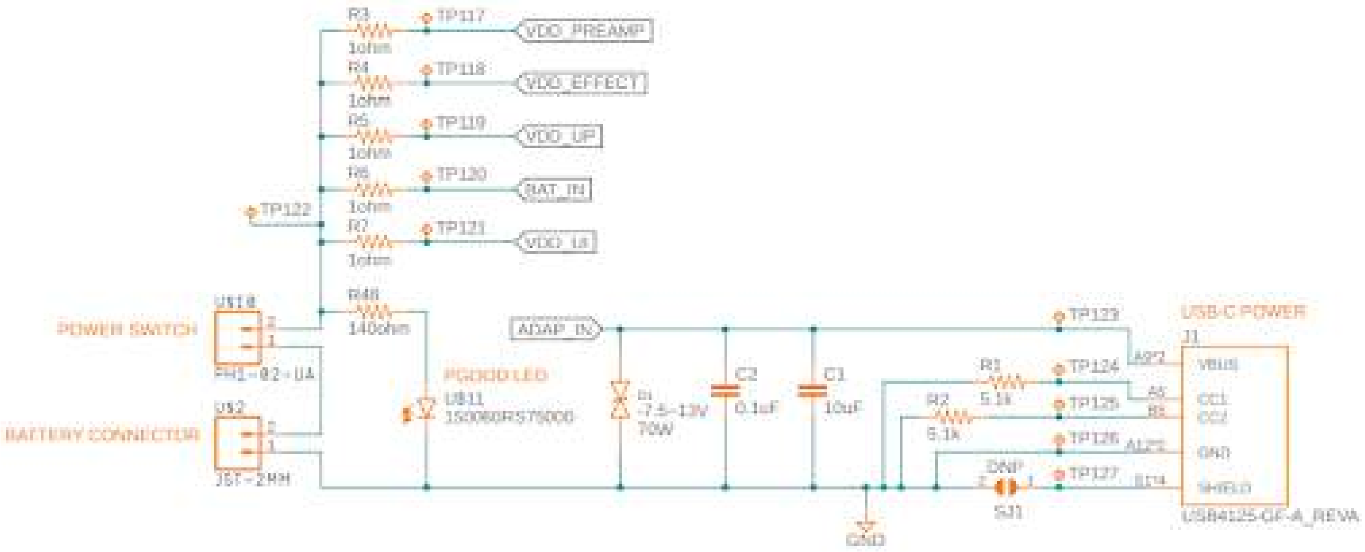


Figure 12: Power Module Schematic

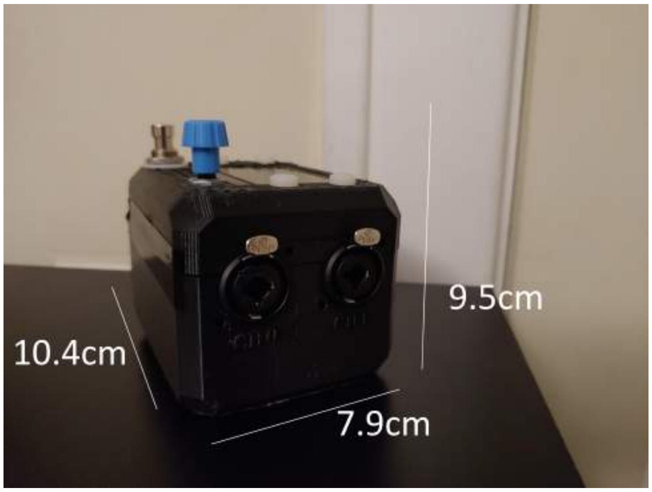


Figure 13: BARI's Dimensions

to meet S.R. 8, this cascade must meet both the maximum attenuation and maximum gain corners. The maximum attenuation corner is attenuating the largest S.R. 6 input signal (1.78 dBV) to -20 dBFS of the ADC (-9.69 dBV). This requires an analog attenuation of -11.47 dB, which is satisfied by the cascade's maximum attenuation of -12 dB. The maximum gain corner is amplifying the smallest S.R. 6 input signal (-60 dBV) to -2 dBFS of the ADC (8.37 dBV). This requires an analog gain of +68.37 dB, which is satisfied by the cascade's maximum gain of +78 dB.

Component	**Min Gain (dB)**	**Max Gain (dB)**
MAX4062	+0	+46
PCM1864 Analog PGA	-12	+32
Cascade	-12	+78

Table 13: Analog Gain Cascade

6.9 Results for S.R. 9 - Pre-Amplifier Gain Flatness

The pre-amplifier circuit achieves excellent gain flatness across the 20 Hz to 20 kHz frequency range, as shown in Figure 14. Gain flatness is better than 0.5 dB, which exceeds our specification of +/- 2dB. The curve below was measured with an input amplitude of approximately 200 mV.

6.10 Results for S.R. 10 - Pre-Amplifier Distortion

S.R. 10 was evaluated by measuring the total harmonic distortion (THD) added by BARI's pre-amplifier over a range of signal magnitudes from 40 to 1,400 mV and a range of frequencies from 20 Hz to 20 kHz. The results of these measurements are shown in Figures 15 and 16.

Some difficulties arose in the evaluation of this system requirement that led to inconclusive results. First, in the measurement of THD vs signal magnitude, the noise floor of our measurement equipment played a significant role. The oscilloscope available to us had a noise floor of approximately -80 dBV (as illustrated by the purple line in

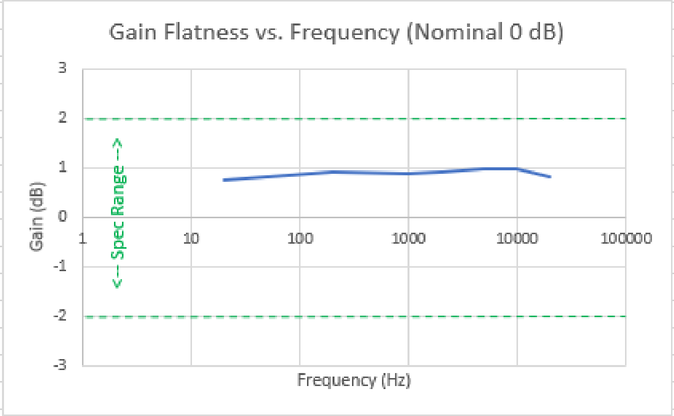


Figure 14: Pre-Amplifier Gain Flatness over Frequency

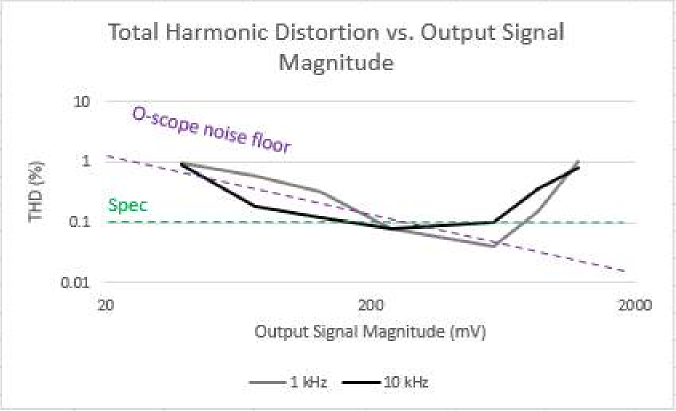


Figure 15: Pre-Amplifier Total Harmonic Distortion vs Input Magnitude

Figure 15). This is much larger than the distortion we were attempting to measure in some cases. For instance, if BARI achieved -60 dBc distortion at an input magnitude of -30 dBV, the resulting distortion would have a magnitude of -90 dBV.

Second, the relative spectral impurity of our test tone source could mask low levels of distortion. See, for example, the "pure sine wave" generated by the DS1104 at a magnitude of 1 V in Figure 17, which contains several high-amplitude spectral components. Particularly at higher frequencies, the lowpass attenuation of these frequency components by BARI exceeded the harmonic distortion introduced by BARI, leading to a non-meaningful negative result for the THD introduced by the pre-amplifier. As a result, only a projection is provided for the higher-frequency values of THD in Figure 16, represented by a dashed line.

6.11 Results for S.R. 11 - Bluetooth Transmission Protocol

We test with a JBL Flip 4, a Sony SRS-XB21, and a Sony WI-C300 Bluetooth speaker/headphone.

We have successfully paired to all the above devices which satisfies our requirement (a). We have Bluetooth

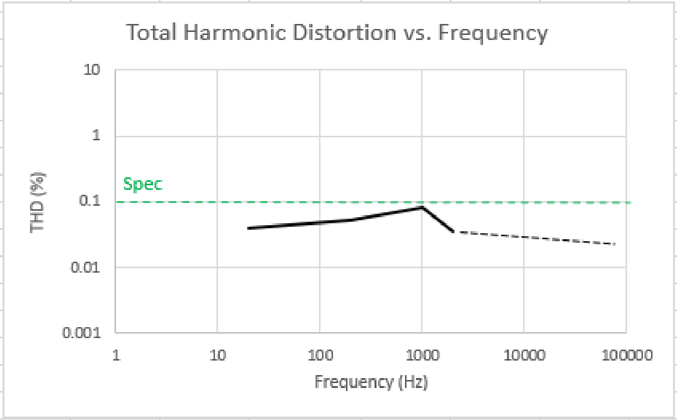
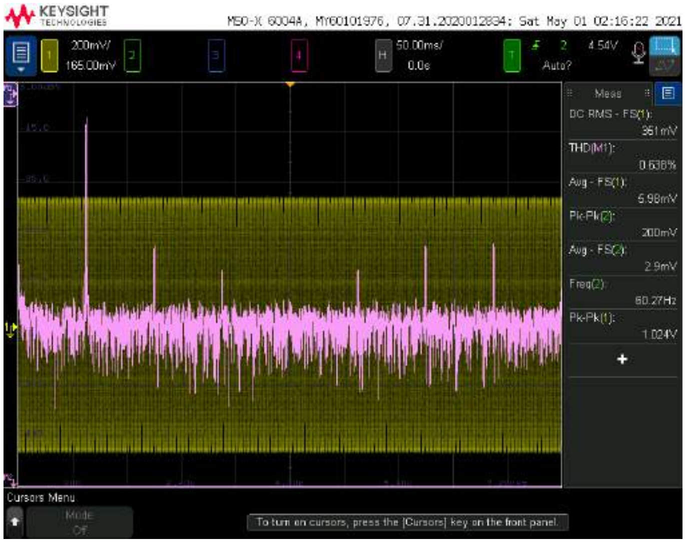


Figure 16: Pre-Amplifier Total Harmonic Distortion vs Frequency (Input Magnitude = 200 mV)



DC RMS - FS(1): 361 mV
THD(M1): 0.636%
Avg - FS(1): 5.98mV
Pk-Pk(2): 200mV
Avg - FS(2): 2.9mV
Freq(2): 60.27Hz
Pk-Pk(1): 1.024V

To turn on cursors, press the [Cursors] key on the front panel.

Figure 17: DS1104 Reference Tone

version 5.0, and A2DP profile, confirmed by the datasheet [2] and the Audio Transceiver Solution firmware we are using [9]. We are currently using the SBC codec, but the BM83 module supports both SBC and AAC, adjustable in the Config Tool as specified in the datasheet [2] and as observed in the graphic user interface of the Config Tool [10].

6.12 Results for S.R. 12 - Bluetooth Transmission Range

We tested by connecting to a Sony WI-C300 Bluetooth headphone, stream music continuously, and moved around while listening to whether the audio changed in the headphone. We tested indoor in a team member's room with approximate dimensions 3m×3m.

- We confirmed that the audio is stable and without loss within the same room (3m×3m).
- We found that the audio starts to be discontinuous (in

other words, the Bluetooth transmission starts to lose packets) at 6m.

6.13 Results for S.R. 13 - Minimum Digital Effects

EQ and Delay have been implemented on BARI, able to be toggled on and off for each channel, meeting the requirement of S.R. 13.

6.14 Results for S.R. 14 - Equalization Quality

EQ filters were designed using equations from Zölzer's text on digital audio signal processing [14]. For verification, plots of the frequency response for each filter were analyzed, as shown in Fig. 18, which shows each type of filter with its minimum and maximum gain settings applied, while the other filters apply no gain. On each plot, the three blue vertical lines are centered at the center frequency of each band, and are from -15dB to +15dB for the center frequency of the band being adjusted and from -5dB to +5dB for the other center frequencies. Based on rough band boundaries, EQ does not meet the required spec of a dynamic range of +/-15dB for an adjusted band without affecting the amplitude of non-adjusted bands by more than +/- 5dB. This could have been achieved by using sharper filters, but may have sounded less natural due to sharper transition points. In particular, the middle frequency control affects the bass frequencies significantly. In qualitative testing, each band's control had the desired affect on the output sound.

6.15 Results for S.R. 15 - Delay Wet/Dry Ratio

The UI allows for adjusting the wet percentage from 0 to 100% in 5% increments, allowing for 20 intermediate tuning steps, meeting the spec of 10 intermediate tuning steps for S.R. 15.

6.16 Results for S.R. 16 - Delay Time

The UI allows for adjusting delay time from 0 to 475ms in 25ms increments, allowing for 19 intermediate tuning steps, meeting the spec of 375ms delay time with 10 intermediate tuning steps for S.R. 16.

6.17 Results for S.R. 17 - Processing Latency

The processing latency is limited by the filling of the input buffer for block processing. The size of each buffer in the input buffer is 32 samples. The ADC samples 24-bit data at 48kHz. To compute latency, multiply 32 samples, 24 bits/samples, and 1/48,000 second/sample, resulting in 1.6ms, meeting the spec of less than 100ms for S.R. 17.

6.18 Results for S.R. 18 - User Interface Response Latency

The limiting factor for responding to user input is the software debounce of the footswitch, which is 200ms. The spec for this requirement has been changed from 100ms to 250ms as 250ms is still a reasonable and barely perceptible delay for system response, but it allows for correct input readings via software debouncing. As such, S.R. 18 is satisfied.

6.19 Results for S.R. 19 - User Interface Update Latency

Update latency is ensured by using a polling routine for UI input updates. The worst-case time for the polling routine is if a footswitch is engaged, resulting in a 200ms update latency, satisfying the 1s update latency for S.R. 19.

6.20 Results for S.R. 20 - User Interface Interaction Time

The setting that requires the most user inputs from the top of the Home menu is Channel 2 Delay, tuning from 0ms to 475ms. A user was timed making this change, with a best time of 4.2s. This time meets the required time of 5s for S.R. 20.

6.21 Results for S.R. 21 - User Interface Feedback Mechanism

A hierarchical menu with a ">" cursor indicating the current menu item was implemented. Menus are included to change any UI system variable, with the relevant system state shown on each menu screen. See Fig. 11 for details. The spec for S.R. 21 is met.

7 PROJECT MANAGEMENT

7.1 Schedule

Our schedule is shown in Fig. 19. The only major change to the schedule was the transfer of UI development from Xingran to Sam.

7.2 Team Member Responsibilities

Adam was primarily responsible for the hardware implementation of BARI. He has downselected most of the hardware components and was responsible for schematic capture, layout, and fabrication of the Rev 1 and Rev 2 PCBs. He was responsible for designing the mechanical enclosure of the device as well as the physical assembly and test of both hardware revisions.

Sam was primarily responsible for the implementation of the digital effects and user interface. For the effects, this included researching the memory usage and feasibility of

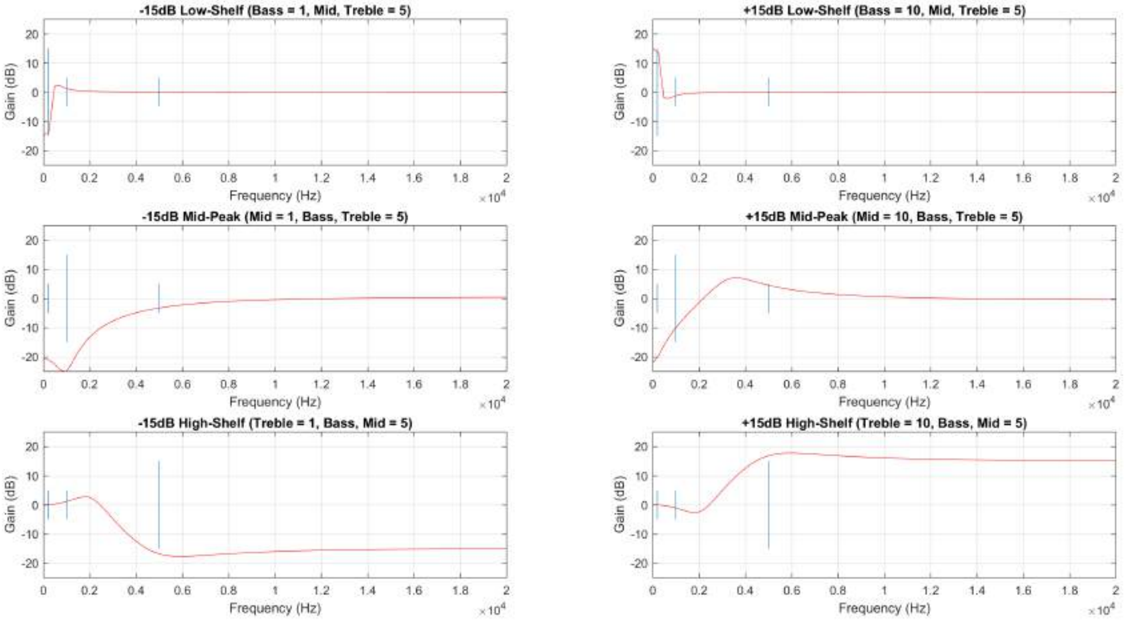


Figure 18: EQ Filter Frequency Responses

DSP effects given the time constraints of the project, researching their implementation, prototyping in MATLAB, implementing them on the STM32 to be used on BARI, and integrating control code to change parameters using the UI. For the UI, this included mocking up a wire-frame, interfacing with the LCD using low-level commands and building libraries to write individual pixels into characters, strings, and then menus. Efforts with the UI also included integrating control code that took user-displayed parameters and converted them into audio path state changes (this was done with Xingran), and interfacing with the rotary encoder with a button and footswitch.

Xingran was primarily responsible for designing the software architecture and control protocols on the microcontroller and the BM83. She implemented the audio signal path from the ADC to the BM83. She set up the microcontroller and implements a set of low-level library functions for controlling all the peripherals, and also the double buffering scheme ready for any DSP algorithm to easily build on top of it. She was also responsible for setting up the programming interface to the microcontroller and the BM83, and helped with hardware testing whenever control from the microcontroller was involved.

7.3 Budget

The overall budget for our project is given in Figure 20. The two sections of the table specify which components are used for development and which are components that are a part of our final product.

Notably, a large fraction of our budget is allocated to the fabrication of our Rev 1 and Rev 2 printed circuit boards. Details of how the budgeted fabrication cost was calculated (and other fabrication options we considered) are presented in a supplemental document at `tinyurl.com/baribudget`. Finally, a bill of materials for the final Rev 2 circuit board is presented in Figure 21.

The cost of BARI remained well within budget, leaving us with a surplus of nearly $150 at the end of the semester.

7.4 Risk Management

The primary risks that we faced in this project were related to hardware verification and system integration schedule.

Our hardware has a longer recovery time if we find any malfunctions in the current version, because it involves manufacturing the PCB which requires at least a week and high budget cost. We mitigated the hardware design risk by splitting our hardware design into two sequential revisions (Rev 1 and Rev 2) with the first scheduled to arrive before the end of March, and the second arriving in late April before the final integration. We have prepared an exhaustive battery of functional tests and bringup procedures (see *BARI Test Procedure*) which we have applied to the Rev 1 board upon receiving it, exposing faults in time for modifications to be made for Rev 2. The Rev 1 board is also designed to be highly reworkable: it is only two layers, with most passive components in 0805 packages or larger and the ability to separate power rails for different modules, making it highly likely that at least some part of the Rev 1 board will be functional despite any hardware glitches.

The Rev 1 / Rev 2 schedule also helps to mitigate our second design risk (system integration) by providing a comparatively long time for integration and test with actual hardware. We have also secured a STM32F4 discovery board that features the same STM32 processor used in our design with many of its peripherals, enabling basic software tests to begin long before the Rev 1 boards arrive. Because the hardware-software interface only really settles after Rev 2 is designed, we developed the software starting from proving the concepts on the discovery board, and then moved on to implementing common interfaces like the I2C and the I2S, and finally worked on controlling the ADC or the Pre-amp after the real hardware arrives. We had some trouble making all the peripherals work and so instead of developing all the functionalities in parallel, we mitigated the scheduling risk by focusing on the MVP and ensured that the ADC and the BM83 work first for the main audio path. We only tested the gain control etc. afterwards.

8 ETHICAL ISSUES

As an entertainment system, the risks posed by BARI to its users and others are inherently limited.

Failure of BARI would mainly impact the user. Particularly if the system failed just before an important event, it could cause significant embarrassment or consternation. That said, the impact of failure is mitigated by the fact that the product is likely only attractive to casual performers. If a performance itself were to have negative externalities (noise complaints, etc.) it's possible that BARI could be partially culpable for enabling it. There are no apparent malevolent uses of BARI.

BARI may not be accessible to certain segments of the population with physical disabilities. For example, those who have impaired vision or fine motor control may find it difficult to operate our user interface.

9 RELATED WORK

BARI's combination of features (low price, connecting to Bluetooth speakers, applying analog and digital effects, and mixing multiple channels) make it unique. However, there are some other products in the marketplace which have a subset of BARI's features.

For example, wireless guitar systems exist which can replace a wired guitar connection with an RF receiver and transmitter. These systems are similar to BARI in that they allow increased mobility for performers, but they do not support connecting to common Bluetooth speakers. An example is the Line 6 Relay G10 [8].

Additionally, many effects pedals exist on the market with various combinations of digital effects. However, these products also lack the ability to connect to a Bluetooth speaker, and they are not cost-competitive with BARI. For example, the Line 6 Helix Floor allows for multiple channels of input and a slew of digital effects, but it is over $1500 MSRP, does not connect to Bluetooth devices, does not have an analog overdrive effect, is almost 15 lbs, and is not powered by a battery [7].

10 SUMMARY

BARI largely meets the requirements we set out for it at the beginning of the semester. As shown in our demo video, the system can accept audio inputs, apply effects to them, and broadcast the resulting signal to common Bluetooth speakers. The poor availability of integrated circuit components in Spring 2021 meant that we were not able to assemble a finalized version of our hardware, but we were able to complete the project with a prototype version of the hardware. The largest outstanding issue is power supply noise from the operation of our Bluetooth Module, which limits our audio signal quality.

If we had additional time to improve BARI, our work would be directed toward the following areas:

- BARI's main circuit board could be respun to eliminate the power supply noise issue noted above. Appropriate mitigation strategies could include using a fully separate power domain for the Bluetooth Module or using differential signaling on-board.
- We could create a better programming method for the Bluetooth Module. Currently the user would still need to use a computer to setup BARI to connect with a Bluetooth speaker, but we could implement simple protocols that make BARI memorize paired speakers and automatically connect upon power up.
- We could implement additional digital signal processing effects, such as chorus, reverb, and wah-wah.
- We could program the Bluetooth Module to fully implement a battery-charging algorithm, allowing the system to be recharged via the USB-C port already placed on the board.

Some important lessons that we learned through the development of BARI this semester include the following:

- Appropriate project scope is a key determining factor in project success. We started the semester with an ambitious proposal that included many subsystems and features, but it was ultimately necessary for us to focus on a Minimum Viable Product with more limited scope in order to achieve a functional demo.
- The global electronics supply chain can be unpredictable. If there are components that you know will be necessary later in the project, it's advantageous to order them before they are needed.

Glossary of Acronyms and Abbreviations

- A2DP - Advanced Audio Distribution Profile

- AAC - Advanced Audio Coding
- ADC - Analog to Digital Converter
- ARM - Advanced RISC Machines
- BARI – Bluetooth Audio Rejiggering Instrument (our product)
- BBD - Bucket Brigade Device
- BJT - Bipolar Junction Transistor
- DAC - Digital to Analog Converter
- dB - Decibel
- dBc - Decibel Carrier
- dBFS - Decibel Full Scale
- DMA - Direct Memory Access
- DSP - Digital Signal Processing
- EQ - Equalization
- GPIO - General Purpose Input/Output
- I2C - Inter-Integrated Circuit Bus
- I2S - Inter-Integrated Circuit Sound Bus
- InAmp - Instrumentation Amplifier
- I/O - Input/Output
- JST - Japan Solderless Terminal
- JTAG - Joint Test Access Group
- LCD - Liquid Crystal Display
- MATLAB - MATrix LABoratory
- MSRP - Manufacturer Suggested Retail Price
- MVP - Minimum Viable Product
- PCB - Printed Circuit Board
- PGA - Programmable Gain Amplifier
- Pre-Amp - Pre-amplifier
- Rev 1 - Revision 1 (original PCB)
- Rev 2 - Revision 2
- SBC - Low-Complexity Subband
- SoC - System on Chip
- SPI - Serial Peripheral Interface
- SPICE - Simulation Program with Integrated Circuit Emphasis
- SQNR - Signal to Quantization Noise Ratio
- SRAM - Static Random-Access Memory
- SWaP - Size, Weight, and Power
- STM32 - Family of 32-bit microcontrollers integrated circuits by STMicroelectronics
- TFT - Thin-Film-Transistor
- TDM – Time-Domain Multiplexing
- THD - Total Harmonic Distortion
- UART - Universal Asynchronous Receiver-Transmitter
- UI - User Interface
- USB - Universal Serial Bus
- USB-C - Universal Serial Bus Type-C
- VDD - Power Supply Voltage
- VSS - Ground Voltage
- WCT - Wireless Concert Technology
- WS - Word Select
- XLR - External Line Return
- ZOUT - Output Impedance

References

[1] Dano (Beavis Audio). *Schematic - Colorsound Overdriver.* URL: `https://http://beavisaudio.com/schematics/Colorsound-Overdriver-Schematic.htm`. (accessed: 05.13.2021).

[2] *BM83 Bluetooth Stereo Audio Module Data Sheet.* C. Microchip Technology Inc. July 2020.

[3] DSPRelated.com. *Peaking Equalizers.* URL: `https://www.dsprelated.com/freebooks/filters/Peaking_Equalizers.html`. (accessed: 05.13.2021).

[4] DSPRelated.com. *Shelving Filter Design.* URL: `https://www.dsprelated.com/showcode/170.php`. (accessed: 05.13.2021).

[5] Analog Devices Inc. *Tutorial: Implementing a Basic Delay Effect.* URL: `https://wiki.analog.com/resources/tools-software/sharc-audio-module/baremetal/delay-effect-tutorial`. (accessed: 05.13.2021).

[6] The MathWorks Inc. *Delay-Based Audio Effects.* URL: `https://www.mathworks.com/help/audio/ug/delay-based-audio-effects.html`. (accessed: 03.17.2021).

[7] Yamaha Guitar Group Inc. *Helix.* URL: `https://line6.com/helix/helix-floor-rack.html`. (accessed: 05.13.2021).

[8] Yamaha Guitar Group Inc. *Relay Wireless*. URL: `https://line6.com/relay-wireless/g10-g10s/`. (accessed: 05.13.2021).

[9] *IS2083/BM83 Bluetooth Applications Design Guide*. B. Microchip Technology Inc. June 2020, pp. 28–40.

[10] Microchip Technology Inc. *IS2083 Turnkey Software and Tools*. Version 1.2.0. URL: `https://www.microchip.com/wwwproducts/en/BM83`.

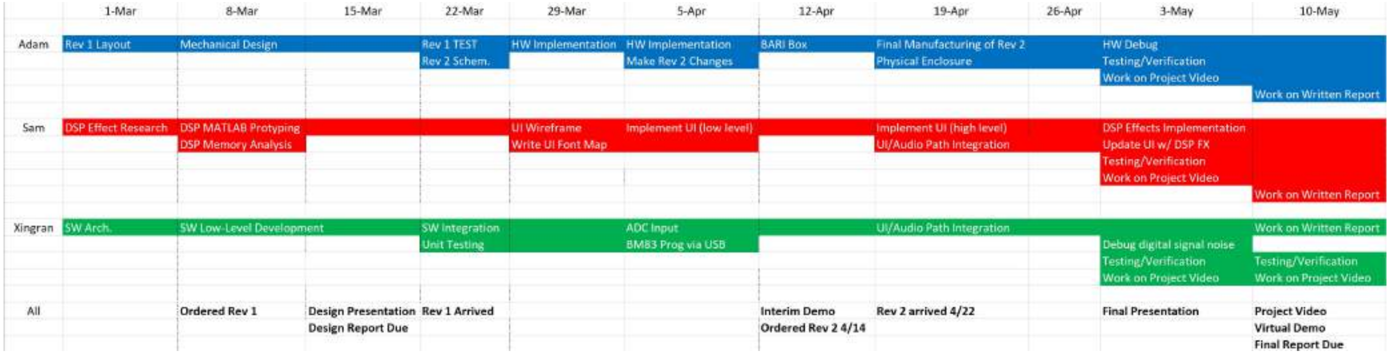
[11] REX Plastics. *The Cost of Injection Molding Materials*. URL: `https://rexplastics.com/uncategorized/the-cost-of-injection-molding-materials`. (accessed: 05.13.2021).

[12] Stanford University. *Direct-Form I*. URL: `https://ccrma.stanford.edu/~jos/fp/Direct_Form_I.html`. (accessed: 05.13.2021).

[13] vader381 (Yuxar Consulting Corp.) *5x8 LCD HD44780U A02 Regular Font*. URL: `https://fonts2u.com/5x8-lcd-hd44780u-a02-regular.font`. (accessed: 05.13.2021).

[14] Udo Zolzer. *Digital Audio Signal Processing*. West Sussex, England: John Wiley & Sons Ltd, 1997.

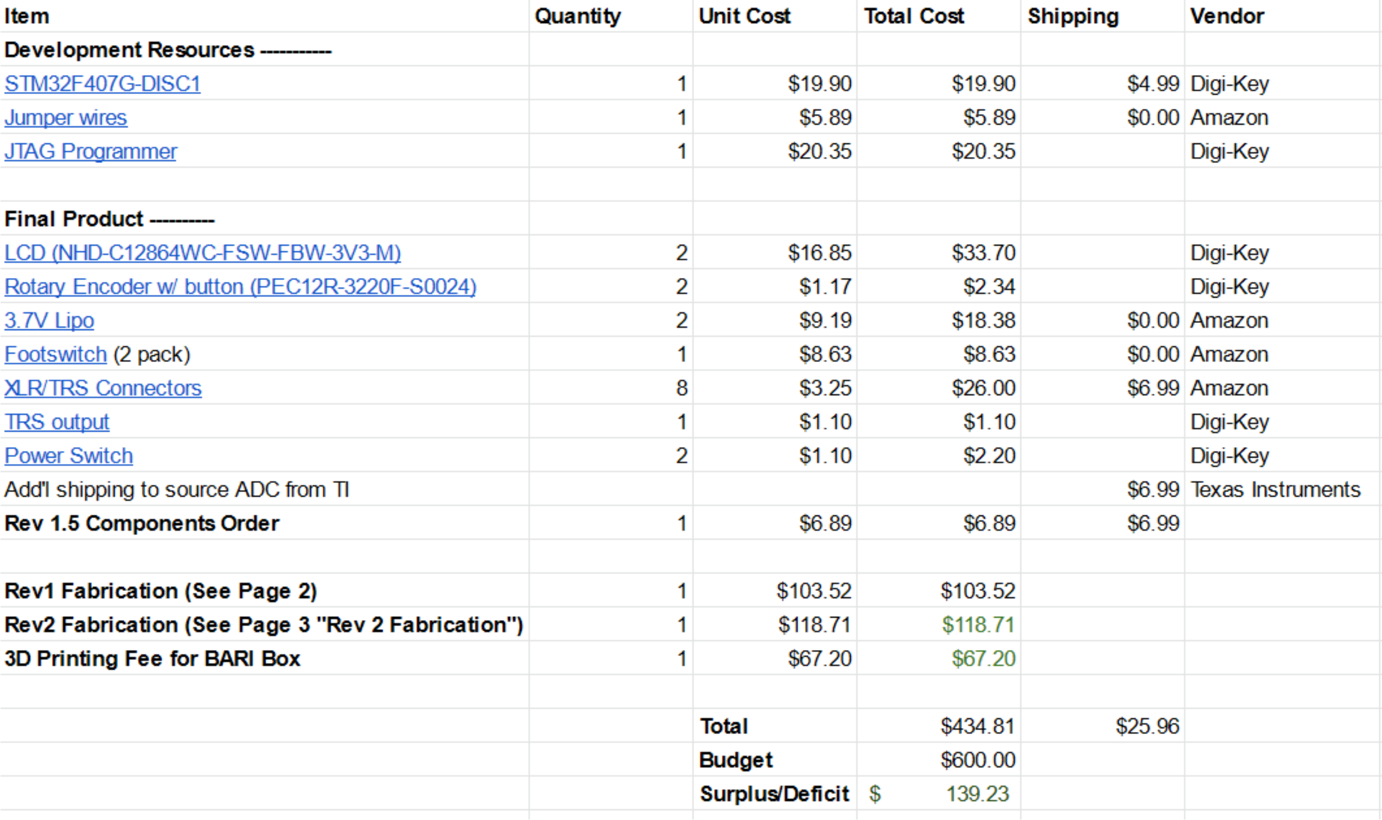
Appendix A



	1-Mar	8-Mar	15-Mar	22-Mar	29-Mar	5-Apr	12-Apr	19-Apr	26-Apr	3-May	10-May
Adam	Rev 1 Layout	Mechanical Design		Rev 1 TEST	HW Implementation	HW Implementation	BARI Box	Final Manufacturing of Rev 2		HW Debug	
				Rev 2 Schem.		Make Rev 2 Changes		Physical Enclosure		Testing/Verification	
										Work on Project Video	
											Work on Written Report
Sam	DSP Effect Research	DSP MATLAB Protyping			UI Wireframe	Implement UI (low level)		Implement UI (high level)		DSP Effects Implementation	
		DSP Memory Analysis			Write UI Font Map			UI/Audio Path Integration		Update UI w/ DSP FX	
										Testing/Verification	
										Work on Project Video	
											Work on Written Report
Xingran	SW Arch.	SW Low-Level Development		SW Integration		ADC Input		UI/Audio Path Integration			Work on Written Report
				Unit Testing		BM83 Prog via USB				Debug digital signal noise	
										Testing/Verification	Testing/Verification
										Work on Project Video	Work on Project Video
All		**Ordered Rev 1**	**Design Presentation**	**Rev 1 Arrived**			**Interim Demo**	**Rev 2 arrived 4/22**		**Final Presentation**	**Project Video**
			Design Report Due				**Ordered Rev 2 4/14**				**Virtual Demo**
											Final Report Due

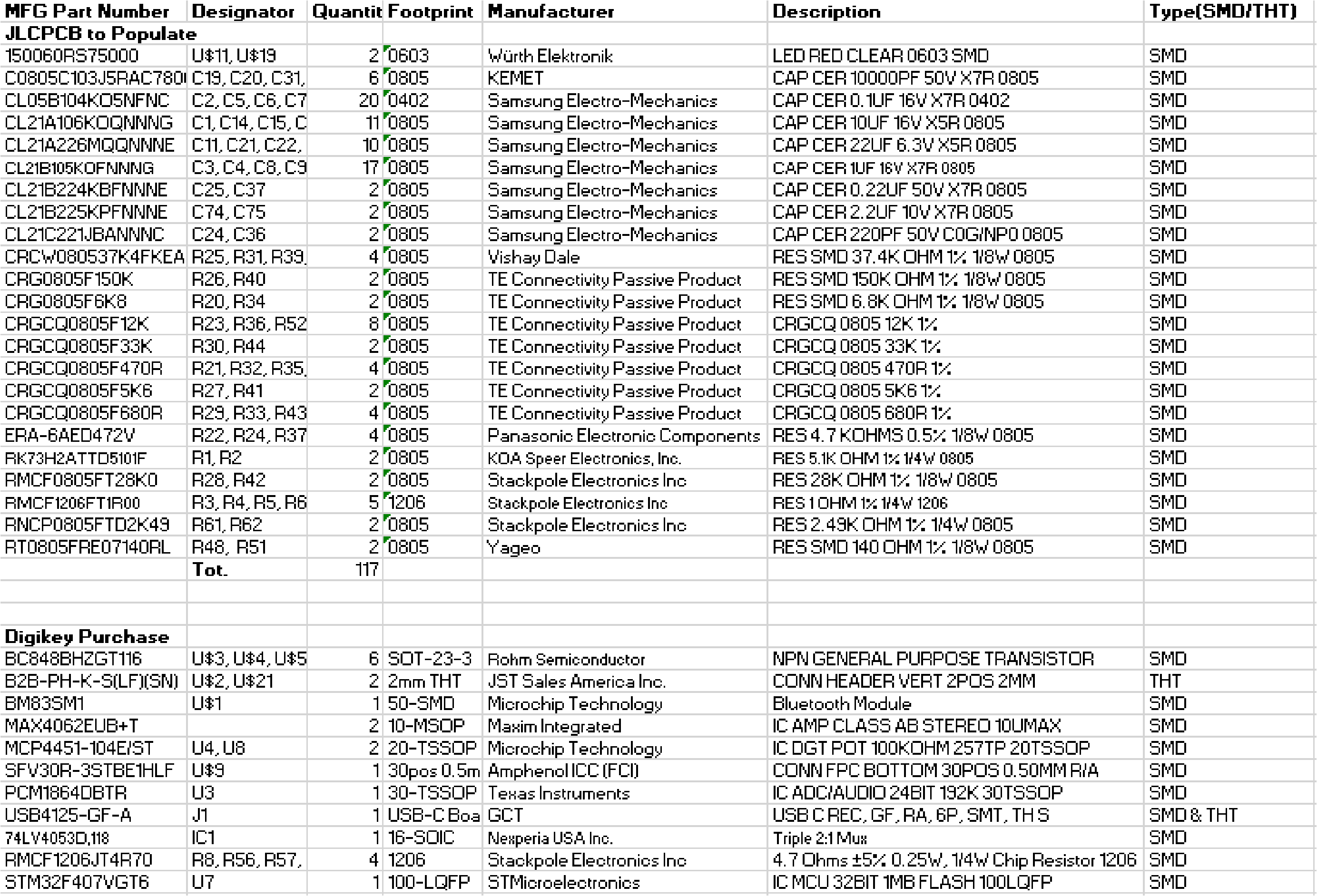
Figure 19: Project Schedule

Appendix B



Item	Quantity	Unit Cost	Total Cost	Shipping	Vendor
Development Resources -----------					
STM32F407G-DISC1	1	$19.90	$19.90	$4.99	Digi-Key
Jumper wires	1	$5.89	$5.89	$0.00	Amazon
JTAG Programmer	1	$20.35	$20.35		Digi-Key
Final Product ----------					
LCD (NHD-C12864WC-FSW-FBW-3V3-M)	2	$16.85	$33.70		Digi-Key
Rotary Encoder w/ button (PEC12R-3220F-S0024)	2	$1.17	$2.34		Digi-Key
3.7V Lipo	2	$9.19	$18.38	$0.00	Amazon
Footswitch (2 pack)	1	$8.63	$8.63	$0.00	Amazon
XLR/TRS Connectors	8	$3.25	$26.00	$6.99	Amazon
TRS output	1	$1.10	$1.10		Digi-Key
Power Switch	2	$1.10	$2.20		Digi-Key
Add'l shipping to source ADC from TI				$6.99	Texas Instruments
Rev 1.5 Components Order	1	$6.89	$6.89	$6.99	
Rev1 Fabrication (See Page 2)	1	$103.52	$103.52		
Rev2 Fabrication (See Page 3 "Rev 2 Fabrication")	1	$118.71	$118.71		
3D Printing Fee for BARI Box	1	$67.20	$67.20		
		Total	$434.81	$25.96	
		Budget	$600.00		
		Surplus/Deficit	$ 139.23		

Figure 20: Project Budget



MFG Part Number	Designator	Quantit	Footprint	Manufacturer	Description	Type(SMD/THT)
JLCPCB to Populate						
150060RS75000	U$11, U$19	2	0603	Würth Elektronik	LED RED CLEAR 0603 SMD	SMD
C0805C103J5RAC780	C19, C20, C31,	6	0805	KEMET	CAP CER 10000PF 50V X7R 0805	SMD
CL05B104KO5NFNC	C2, C5, C6, C7	20	0402	Samsung Electro-Mechanics	CAP CER 0.1UF 16V X7R 0402	SMD
CL21A106KOQNNNG	C1, C14, C15, C	11	0805	Samsung Electro-Mechanics	CAP CER 10UF 16V X5R 0805	SMD
CL21A226MQQNNNE	C11, C21, C22,	10	0805	Samsung Electro-Mechanics	CAP CER 22UF 6.3V X5R 0805	SMD
CL21B105KOFNNNG	C3, C4, C8, C9	17	0805	Samsung Electro-Mechanics	CAP CER 1UF 16V X7R 0805	SMD
CL21B224KBFNNNE	C25, C37	2	0805	Samsung Electro-Mechanics	CAP CER 0.22UF 50V X7R 0805	SMD
CL21B225KPFNNNE	C74, C75	2	0805	Samsung Electro-Mechanics	CAP CER 2.2UF 10V X7R 0805	SMD
CL21C221JBANNNC	C24, C36	2	0805	Samsung Electro-Mechanics	CAP CER 220PF 50V C0G/NP0 0805	SMD
CRCW080537K4FKEA	R25, R31, R39,	4	0805	Vishay Dale	RES SMD 37.4K OHM 1% 1/8W 0805	SMD
CRG0805F150K	R26, R40	2	0805	TE Connectivity Passive Product	RES SMD 150K OHM 1% 1/8W 0805	SMD
CRG0805F6K8	R20, R34	2	0805	TE Connectivity Passive Product	RES SMD 6.8K OHM 1% 1/8W 0805	SMD
CRGCQ0805F12K	R23, R36, R52	8	0805	TE Connectivity Passive Product	CRGCQ 0805 12K 1%	SMD
CRGCQ0805F33K	R30, R44	2	0805	TE Connectivity Passive Product	CRGCQ 0805 33K 1%	SMD
CRGCQ0805F470R	R21, R32, R35,	4	0805	TE Connectivity Passive Product	CRGCQ 0805 470R 1%	SMD
CRGCQ0805F5K6	R27, R41	2	0805	TE Connectivity Passive Product	CRGCQ 0805 5K6 1%	SMD
CRGCQ0805F680R	R29, R33, R43	4	0805	TE Connectivity Passive Product	CRGCQ 0805 680R 1%	SMD
ERA-6AED472V	R22, R24, R37	4	0805	Panasonic Electronic Components	RES 4.7 KOHMS 0.5% 1/8W 0805	SMD
RK73H2ATTD5101F	R1, R2	2	0805	KOA Speer Electronics, Inc.	RES 5.1K OHM 1% 1/4W 0805	SMD
RMCF0805FT28K0	R28, R42	2	0805	Stackpole Electronics Inc	RES 28K OHM 1% 1/8W 0805	SMD
RMCF1206FT1R00	R3, R4, R5, R6	5	1206	Stackpole Electronics Inc	RES 1 OHM 1% 1/4W 1206	SMD
RNCP0805FTD2K49	R61, R62	2	0805	Stackpole Electronics Inc	RES 2.49K OHM 1% 1/4W 0805	SMD
RT0805FRE07140RL	R48, R51	2	0805	Yageo	RES SMD 140 OHM 1% 1/8W 0805	SMD
	Tot.	117				
Digikey Purchase						
BC848BHZGT116	U$3, U$4, U$5	6	SOT-23-3	Rohm Semiconductor	NPN GENERAL PURPOSE TRANSISTOR	SMD
B2B-PH-K-S(LF)(SN)	U$2, U$21	2	2mm THT	JST Sales America Inc.	CONN HEADER VERT 2POS 2MM	THT
BM83SM1	U$1	1	50-SMD	Microchip Technology	Bluetooth Module	SMD
MAX4062EUB+T		2	10-MSOP	Maxim Integrated	IC AMP CLASS AB STEREO 10UMAX	SMD
MCP4451-104E/ST	U4, U8	2	20-TSSOP	Microchip Technology	IC DGT POT 100KOHM 257TP 20TSSOP	SMD
SFV30R-3STBE1HLF	U$9	1	30pos 0.5m	Amphenol ICC (FCI)	CONN FPC BOTTOM 30POS 0.50MM R/A	SMD
PCM1864DBTR	U3	1	30-TSSOP	Texas Instruments	IC ADC/AUDIO 24BIT 192K 30TSSOP	SMD
USB4125-GF-A	J1	1	USB-C Boa	GCT	USB C REC, GF, RA, 6P, SMT, TH S	SMD & THT
74LV4053D,118	IC1	1	16-SOIC	Nexperia USA Inc.	Triple 2:1 Mux	SMD
RMCF1206JT4R70	R8, R56, R57,	4	1206	Stackpole Electronics Inc	4.7 Ohms ±5% 0.25W, 1/4W Chip Resistor 1206	SMD
STM32F407VGT6	U7	1	100-LQFP	STMicroelectronics	IC MCU 32BIT 1MB FLASH 100LQFP	SMD

Figure 21: Rev 2 (Final) PCB Bill of Materials