Bachelor Project

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F3

Faculty of Electrical Engineering
Department of Measurement

Guitar digital effect

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Supervisor: Prof. Ing. Jan Holub, Ph.D.
Field of study: Electrical Engineering
Subfield: Cybernetics and Robotics
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Declaration

I hereby declare that I have worked on this thesis independently and specified all the used information sources in accordance with the Methodical guidelines about following ethical principles during the preparation of university theses.

In Prague, 7. May 2021

Jakub Turinský

Abstract

The thesis dedicates to designing a digital guitar pedal delivering a large variety of sounds that can also function as a developing platform. The core of the project is based on sound processor FV-1 from Spin Semiconductor company. Developing different bypassing options with interesting results such as Attiny85 processor-controlled relay bypass with pop-sound muting, processor-controlled silent buffered bypass with natural recorded signal fade out, true bypass, or simple buffered bypass all possible in one pedal. The digital effect is adjustable by five potentiometers. Effect control substitutable by an external expression pedal, overall volume control, and three FV-1 user input controls. Effect unit includes analog effect module slot with separate bypass switching and controls for combining digital and analog effects in many different ways. The pedal offers a selection of eight internal and eight custom external programs stored in EEPROM memory reprogrammable by a custom USB programmer. Other than a custom USB programmer, the thesis includes an Attiny programmer shield for Arduino UNO and a simple oscilloscope shield for Leo oscilloscope.

Keywords: Guitar pedal effect, digital audio effect, delay effect, bypass switching, FV-1, Attiny85

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Abstrakt

Práce se zabývá návrhem digitálního kytarového pedálu přinášejícího mnoho různých možností zvukových efektů, který může sloužit i jako vývojová platforma. Jádro projektu je založeno na zvukovém procesoru FV-1 od firmy Spin Semiconductor. Dále se zabývá vývojem různých bypass možností se zajímavými výsledky jako procesorem řízené relé spínání s mutováním cvaknutí při přepnutí, řízený nehlučný buffered bypass s přirozeným dozněním nahraného signálu, true bypass nebo jednoduchý buffered bypass s možností zapojení všech možností. Digitální efekt je nastavitelný pěti potenciometry. Effect potenciometr nahraditelný externím expression pedálem, Volume potenciometr nastavující celkovou výstupní hlasitost a tři potenciometry jako uživatelské vstupy FV-1. Efekt obsahuje patici pro analogový efektový modul s vlastním bypass spínáním a potenciometry pro kombinování digitálního a analogového effectu v mnoha různých kombinacích. Pedál nabízí výběr mezi osmi interními a osmi vlastními externími programy, které jsou uloženy v EEPROM paměti přeprogramovatelné navrhnutým externím USB programátorem. Mimo vlastní USB programátor, byl navržen programátor Attiny procesoru jako shield pro Arduino UNO a jednoduchý shield pro Leo osciloskop.

Klíčová slova: Kytarový pedálový efekt, digitální audio efekt, delay efekt, bypass spínání, FV-1, Attiny85

Překlad názvu: Digitální kytarový efekt

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BACHELOR‘S THESIS ASSIGNMENT

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[2] Dokumentace k vývojovému kitu SPN1001-DEVB

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III. Assignment receipt

The student acknowledges that the bachelor’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor’s thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt	Student’s signature

Part I

Introduction

Chapter 1

Introduction

This project aims to design a fully functioning digital guitar pedal that can serve as a traditional guitar effect for musicians and as a developing platform for audio effects. The outcome audio device has to be reliable and durable, so it needed to be designed into PCB with consideration of possible future serial production and the possibility of easy and reliable reprogramming of the sound processor programs. It will be powered and connected into a signal

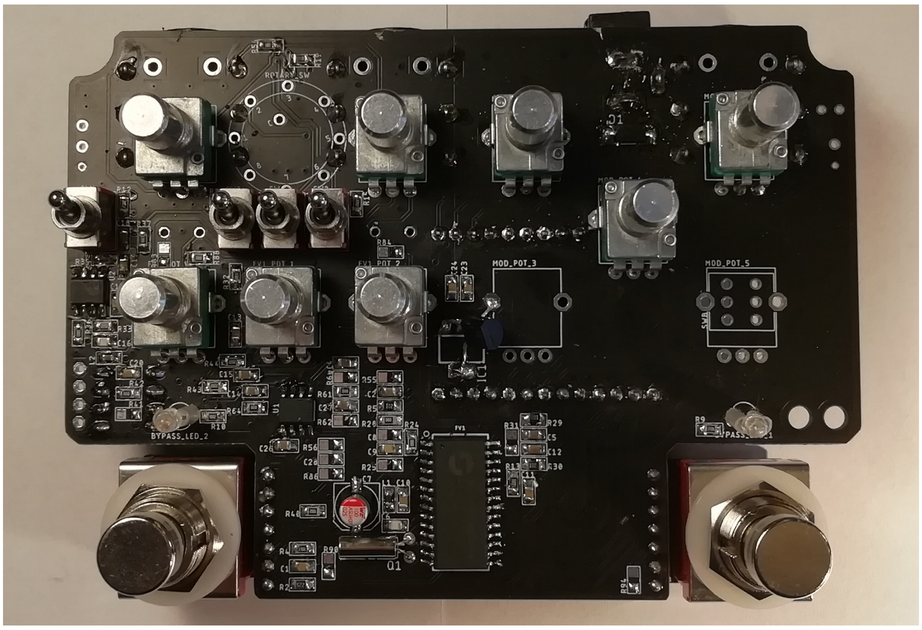


Figure 1.1: Top view of the fully assembled digital guitar pedal with true bypass switching.

chain by standard pedal effect gear and needs to include different bypass possibilities (true bypass, buffered bypass, controlled bypass). The core of the finished pedal will be based around the FV-1 sound processor with enabling most of the features. It will include a slot for an effect module that I designed with the KHDK company. The project will not include audio effect program design and will be tested on open source programs available online [9].
In Part I Introduction, I go from designating sound effect types that the digital effect circuit should reproduce to laying down the basic electronic requirements, including uncommon features and layout of the device. In Part II Digital guitar pedal, I choose the sound processor, design of the main circuit, design of the PCBs, design of the external hardware for the pedal, including a custom USB programmer for easy reprogramming without removing the EEPROM. In Part II, there are discussed and solved problems that occurred while designing, for example, silent buffered bypass switching with natural repeat fade out. In Part III Results and the conclusion, I go through assembling and testing the pedal, measuring the transfer functions of the pedal in different modes, conclude the pros and cons, and discuss further development. This project was designed in cooperation with the KHDK guitar pedal company, mainly with KHDK's sound engineer Antonín Salva.

Figure 1.2: Angled top view of the fully assembled digital guitar pedal in enclosure with True bypass switching.

Chapter 2

Generall informations about guitar pedals

Guitar pedals (or effect units) are electronic devices that plug into the signal chain between the guitar and the amplifier or into an effect loop of the amplifier, which is a signal path between the preamplifier and power amplifier. They stack after each other in series or can be used to split signals into two or more amplifiers. Usually, they are constructed into a stompbox, into a rack, or integrated into amplifiers (an example is a reverb found in many amplifiers). Most common are effect pedals in stompboxes because of their practical advantages (you can easily change the order of the effects to produce different sounds or easily switch them with different ones). Stompboxes are usually enabled/bypassed by footswitch. For some occasions, stompbox pedals can be put into the rack shelf. Then the musician can enable/bypass remotely via an external looper pedal that controls the effect in chains at once. External looper is a more expensive and complex way of setting up the signal effect chain. However, it enables possibilities of enabling several guitar pedals at once, and many musicians prefer it.

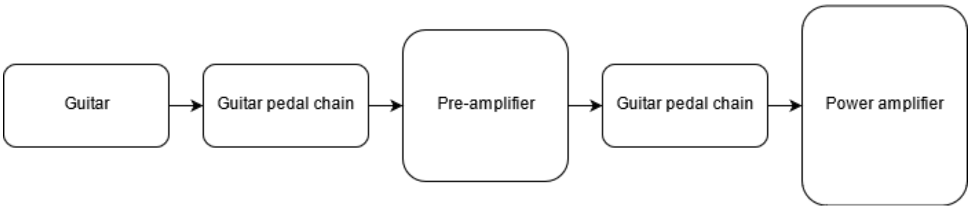


Figure 2.1: Example of signal guitar signal chain with effect loop.

2.1 Guitar effect types

I will go through some typical guitar pedal effects and how they could be constructed analog and digital. There are many different guitar pedal types, so that I will mention only the most common. Musicians often prefer analog circuits for effects that can be done cheaply analog.[10] Therefore, if there is a way for an analog solution that is cheap with high quality, and reliable, they will not be included in the design. Most of the information below is general knowledge, but I will go through them to give better context to the pedal design.

2.1.1 Distortion effects

(a) : Typical soft clipping distortion (overdrive) effect pedal - Ibanez Tubescreamer TS808.[11]

(b) : Typical hard clipping distortion (distortion) effect pedal - Proco Rat 2 Distortion.[12]

Figure 2.2: Distortion pedals examples.

The distortion effect works by clipping the signal creating distortion adding higher harmonics to the signal. There are several ways to clip the signal. Guitar pedals usually use diodes/LEDs to clip the signal. Most common are soft-clipping guitar pedals (commonly called overdrive pedals) that use anti-parallel diodes in the feedback loop of an operational amplifier set as a non-inverting amplifier with controlled amplification. [13]
Distortion pedals are usually very simple analog circuits that are very cheap to construct, so there is no need to make them digitally. Therefore I won't consider editing the effect circuit to serve as a distortion. I chose a soft clipping overdrive effect for the analog effect module, see in section 7.8.

2.1.2 Dynamic effects

(a) : Active booster effect pedal example - Xotic EP Booster.[14]

(b) : Active equalizer effect pedal example - Boss GE-7 Equalizer.[15]

Figure 2.3: Dynamic and filter effects example.

Volume or boost pedals are called Dynamic pedals because they modify the amplitude of the signal. They can be constructed as passive volume pedals or as active (powered) boost pedals, amplifying the signal. Passive volume/expression works as a basic voltage divider constructed into mechanical enclosures that are adjustable by foot, enabling much variety in sound. In contrast to the distortion effects, active boost pedals are constructed to minimalize signal distortion with high overall gain. Boost pedals are usually constructed with some frequency filter to boost or cut off some frequency range, but it is not their main purpose.
The dynamic effect can be made very easily and cheaply by an analog circuit, so there is no need to make them digitally. Passive volume pedals can be used as user input extensions for pedals and can expand pedal possibilities (more about this topic in requirements chapter 3).

2.1.3 Filter effects

Filter effects work very similarly to dynamic effects, with the difference that they are constructed to boost or cut off specific frequency bandwidths. They can be designed like a classic multiple bandwidth equalizer, expression-controlled active RLC filter (for example, wah-wah effect), parametric EQ, etc.
Filter effects can be made very easily and cheaply by an analog circuit. Therefore, there is no need to make them digitally.

2.1.4 Modulation effects

For guitar effect pedals, modulation stands for controlling/alternating some effects strength or tone in time. An example of a modulation effect is changing the gain of some filter bandwidth in time by reference voltage of a function generator like a sine wave with adjustable frequency and amplitude. There are many types of modulation effects, but I will mention only the four most common ones: chorus, flanger, tremolo, and vibrato.

The Chorus effect simulates multiple instruments playing at the same time. It works by mixing a dry signal with a processed signal that has a slightly offset pitch. The offset is controlled by a wave signal that commonly has an adjustable frequency (rate) and amplitude (depth). Flanger works similar to the chorus. It works by mixing a dry signal with a processed signal that is very little (less than 20ms) delayed. The delay is changing controlled by a wave signal that usually has an adjustable frequency (rate) and amplitude (depth). Tremolo is an effect created by changing the amplitude gain of the input signal in time by wave signal, usually with adjustable frequency (rate) and amplitude (depth). Vibrato is a very similar effect as the chorus effect but with usually higher frequency without the dry signal mixed to the output.

The most common way of making analog modulation pedals is based on electromechanical machines such as tape recorders set as delays and have, for example, delay parameters operated by the oscillator. Tape recorders are very fragile to mechanical defect when transporting or using and are very expensive to make, so the best way (cheap and reliable) is to make them digitally.

(a) : Chorus effect pedal example - Electro Harmonix Small Clone EH 4600 Full-Chorus.[16]

(b) : Pitch shift/octaver effect pedal example - Digitech The Drop.[17]

Figure 2.4: Modulation and pitch/frequency based effect pedal examples.

2.1.5 Pitch/frequency effects

The effect that changes the pitch is often classified as pitch or frequency effects. The typical pedal effect would be pitch shift or octaver. Pitch shift shifts the signal frequency up or down and usually is installed into a mechanical enclosure similar to a volume pedal for control by foot. Octaver adds to the dry signal another signal or signals shifted by some number of octaves (for example, it doubles/halves frequency of the dry signal) up or down. This effect is often used because it offers a large variety of sounds.

The best way to design pitch/frequency effect is with a digital approach. Therefore I will include and test them in this project.

2.1.6 Time based effects

Pedals that recreate signal on the output with time-shift are called time-based effects. The most common time-based pedal is a delay. Delay records signal on the input and recreate it on the output with time delay and repeat it for some number of repeats with decay fading the echos away. Another time-based effect is reverb. Reverb simulates echo in large rooms, for example, concert hall. It works similar to the delay pedal but with many short echoes that fade away slowly so that there is not the sharp sound of a delay.

Time-based pedals can be made analog but very difficult and fragile. Analog delays are usually based on some electromechanical recorder like tape recorders that record the sound and repeat it on the output 2.5. These are very expensive to build and fragile to operate, so the audio processor often supplements them. Analog reverbs are sometimes made as spring reverbs that work by input signal transforming into mechanical vibrations transmitted via spring to a sensor that is then amplified and reproduced. These are very fragile again to mechanical interruptions because they receive all mechanical vibrations, for example, from the floor, and they are significantly physically larger than most of the stompbox pedals. They are still used integrated into amplifiers but can be done cheaper and more reliable digitally.

As an analog delay are called pedals that use BBD (Bucket Brigade Delay) chips [18, 19]. They work by storing the electrical charge of the input signal. The charge goes through the chip at the rate of an external clock. This way, they store the analog value of the signal but have many disadvantages. It resolves in a good amplitude resolution, but the clock creates much noise on the output. [20] They are used in most analog delays that are available on the market marked as analog delay and not as tape delay or spring delay. [21]

Time-based effects are the most common effects for digital processing. Therefore, they will be the main effect outcome of this bachelor thesis.

Figure 2.5: Example of a tape echo - Roland RE-201 Space Echo.[1]

Chapter 3

Guitar effect pedal requirements

3.1 Guitar effect design requirements

Guitar pedals are widely used devices for guitar signal processing. To make it easier for the guitar player to use them there are a few design rules that need to be met, so the outcome design is usable, and some features I want to include.

3.1.1 Powering

Most of the guitar pedals are powered by DC power. The most common powering is by 9V DC jack with the ground on the inside pin with 2.1mm shaft and 9V pin on the outer ring. Most of the power supplies for the guitar pedals are designed to produce DC power this way, so a good habit is to design the guitar pedal power input the same way to avoid using reduction or damaging the circuit. The typical power supply for guitar pedals is a DC power source with multiple galvanically isolated outputs that can produce 9V with around 300mA output current, see on figure 3.1.
Another common way is to use a 9V battery for power. Although the battery cannot handle the pedal running for a long time and changing it often gets expensive, it is a practical solution for a few situations. The most common situation for powering a guitar pedal by a battery is in the studio. Even tho power supplies have filtering of the grid (50Hz) noise, it can still be audible

with some high gain amplification. For this reason, the battery is often used for studio recording for a cleaner output.
For this design, it will combine both. This way, the user can choose different ways to power the pedal in different situations. This method is common with guitar pedal designs.

Figure 3.1: Example of guitar pedal power supply.[2]

3.1.2 Connectors

Guitars, pedals, and amplifiers are designed to connect with 6.3mm mono jack audio cables with a male connector on each side. My guitar pedal will be connected the same way with 6.3mm jack female connectors as input and output.

3.1.3 Enclosure

To reduce high-frequency noise like radio waves receiving and amplifying it to output, guitar pedals are closed in grounded metal (aluminum) enclosures that serve as shielding. It also helps to prevent mechanical damage. I chose Hammond 1590BB as the enclosure for my pedal (see on figure 3.2).

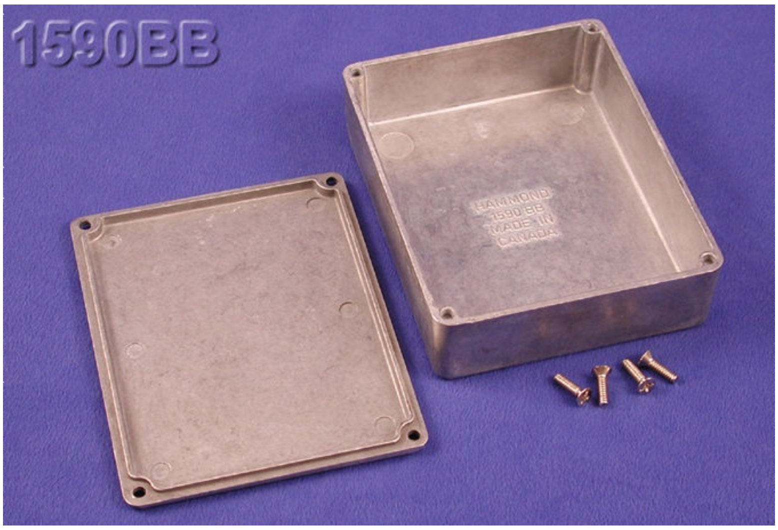


Figure 3.2: Chosen enclosure Hammond 1590BB.[3]

3.1.4 Switching

Guitar pedals usually lay down on the ground and are toggled by stepping on a switch so the musician can do it while playing. This means that the switch needs to be durable and to be toggled by force pressing on it. Some guitar pedal manufacturers design their mechanical parts that convert the force press to a simple button. I will use the most common switches and buttons that are designed to be toggled by pressing them by foot. I chose two different ones for different use. 3PDT footswitch for true bypass switching and normally open momentary switch as an input for Attiny processor-controlled bypass switching (see on figure 3.3).

(a) : 3PDT footswitch.[22] **(b) :** Momentary footswitch.[23]

Figure 3.3: Footwitch options used in design.

3.1.5 Bypassing the effect

The pedal has on/off mode. When the effect is off, the input signal goes to the output. When on the input goes to the effect in and from effect out to the output. Based on how the signal goes through the bypassed pedal, there are two different possibilities: true bypass and buffered bypass.
True bypass is when the input and output are connected only via physical metal connection when off. This way, the bypassed pedal affects the signal least, which is often desired. A typical problem of the true bypass is that the mechanical switch produces pop noise when toggled.[24]
Buffered bypass is when the input signal is split in the pedal to dry and wet signal. The signal typically goes through some buffer to prevent signal loss. The on/off switches by interrupting dry/wet signal. This way, the signal is affected by the buffer, which can or cannot be desirable. Simple buffered bypass is commonly less expensive (interrupting/connecting the signal by JFET and operating the on/off state by flip flop circuit) and has no click (pop) noise.[24]
My pedal will have the ability to be assembled as true bypass and as buffered bypass as well. Bypassing the effect will be on the FV-1 and the module separately. More about this topic in chapter 5 Circuit design.

3.1.6 Effect module slot

The guitar pedal will have a slot for the guitar effect module that I designed with KHDK company. This way, it can be assembled into a double pedal, for example combination of FV-1 based delay pedal and analog overdrive.

3.1.7 Expression/volume pedal slot

I want the pedal to have a slot for the expression pedal to control the pedal for my design. The expression pedal is a potentiometer that is controlled by foot. Foot rests on a surface that can be angled from the ground. The angle is either transferred to the potentiometer via some mechanical transformer directly or via some distance measuring sensor controlling the output resistance. The output is then a stereo 6.3mm jack with potentiometer/controlled resistor pins connected to the cable contacts.
It works as a simple voltage divider on the signal path. The volume pedal works by plugging into the signal path with in and out mono cables. The

expression pedal works very similarly, but all of the three pins of the potentiometer connect to one stereo cable. To make the volume pedal into the expression, use two mono into stereo 6.3mm jack reduction.

Figure 3.4: Example of the volume pedal with mechanical angle transfer: Ernie Ball EB6180 VP-JR [4].

3.1.8 Controls and input/output layout

Guitar pedal is typically used in a pedalboard, a type of mechanical construction where you put your pedals and plug them in series. For this case, it's most practical to have the DC power slot and input/output slot on top of the pedal so the cables can plug in easily and they do not physically interfere with each other. Guitar pedals have the input on the right side and output on the left side. This rule needs to be set so the signal path can be connected easily in series.

Controls (potentiometers and switches) placing is on the top surface in the top half of the pedal. Since the pedal can be assembled as a double pedal and the typical F-V1 pedal will be a delay, reverb, etc., which typically comes last in the signal chain, and the module will be mostly some booster which typically comes first in an effect chain, the controls will be split. The module on the right (on the input side), FV-1 pedal on the left (output side).

The bypass switch which turns the pedal on/off when stepped on needs to be located on the bottom of the front panel, so the user does not damage or change the controls by foot.

An example of the layout is on picture 3.5. More about this topic in chapter

6 PCB design.

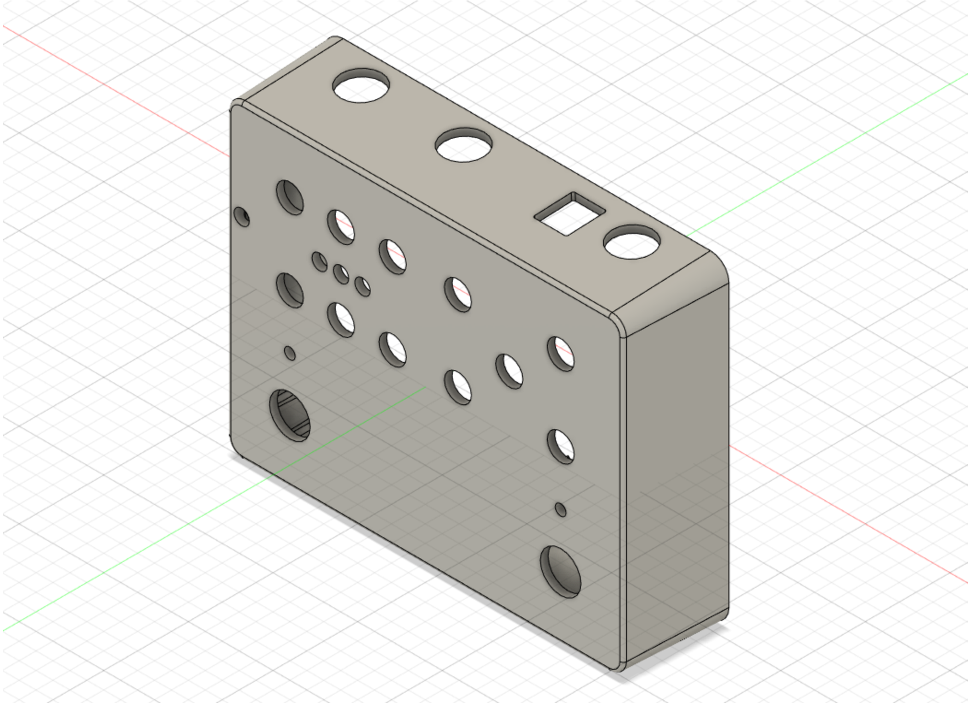


Figure 3.5: First drawing of the pedal layout, empty 3D model of the Hammond 1590 enclosure is from Hammond manufacturing [3].

Part II

Digital guitar pedal design

Chapter 4

Sound processor selection and first development board

One of the goals of the thesis is to find the best compromise of price, audio record quality (high resolution of ADC/DAC and high sampling frequency), memory size, and variability.

4.1 Sound processor selection

Here I will briefly show another sound processing possibility I considered for the digital guitar pedal design.

4.1.1 Preprogrammed sound processors - Pt2399

A typical low price example of a preprogrammed sound chip for digital guitar pedals is PT2399 4.1. [21] It is a single chip preprogrammed echo processor which can be used as echo or delay (circuit examples in documentation [25]). It is a sound processor made by Princeton technology corp. in THT and SMD packages. The advantage of PT2399 is the simplicity of the circuit (reducing the overall cost of the device). The major disadvantage of this chip is its lack of program customization and low memory size (44Kbit RAM). PT2399 offers delay time configuration by setting resistor value on pin 6 to

Figure 4.1: PT2399[5].

the GND (see in documentation [25]). Pt2399 does not offer enough audio effect versatility for this project.

4.1.2 Processor with separate AD/DA convertors

This option would offer the most versatility with guitar pedal design, but the cost and complexity are a significant disadvantage, so I decided to go with a different option. [26]

4.1.3 Programmable sound processor - FV-1 sound processor

Another option is the FV-1 sound processor from Spin Semiconductor [6], that comes only in the SMD package. Advantages of this sound processor are that it offers eight internal demonstrational programs and easy customization with external EEPROM memory, which can contain another eight custom programs, integrated stereo ADC/DAC, three potentiometer inputs for real-time parameter adjustment and 512Kbit RAM for recorded signal. The main disadvantage is the price. FV-1 costs approximately 300czk for a piece [27] in a small amount order but gets cheaper with larger amounts.

Figure 4.2: FV1 sound processor[6].

With all of its advantages and disadvantages, I decided to use this sound processor with my design.

4.2 Search for available development kits

I chose to use some development kit with the FV-1 sound processor installed to start designing guitar pedals. I require it to be an open-source dev kit so that I can use it as a starting point for my development kit if it will not cover all of my feature requirements.

4.2.1 SPN1001-DEV

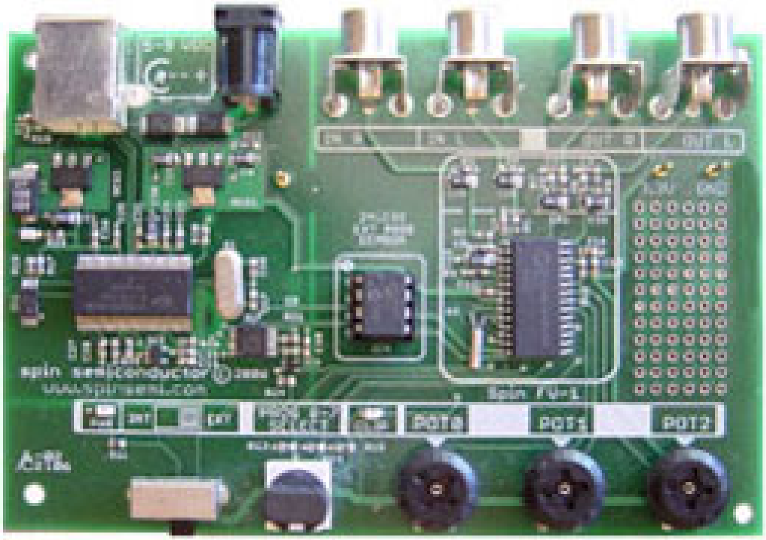


Figure 4.3: SPN1001-DEV[6].

SPN1001-DEV is an open-source development board from Spin Semiconductor with an integrated programmer for the EEPROM with external programs. It offers use of the internal and external EEPROM programs by switching between them with rotary switch, all three potentiometers for the user changing internal parameters, stereo input and output with cinch connectors, power delivery by USB or with an external adapter.
The major disadvantage of this development kit is its price, which is approximate 2500czk [28]. Another disadvantages are that it does not have input and output buffers for signals setting the input and output impedances, does not include dry signal path and mix on the output, and does not have standard

(for guitar pedals) 6.3mm jack input and output (see in figure 4.3).

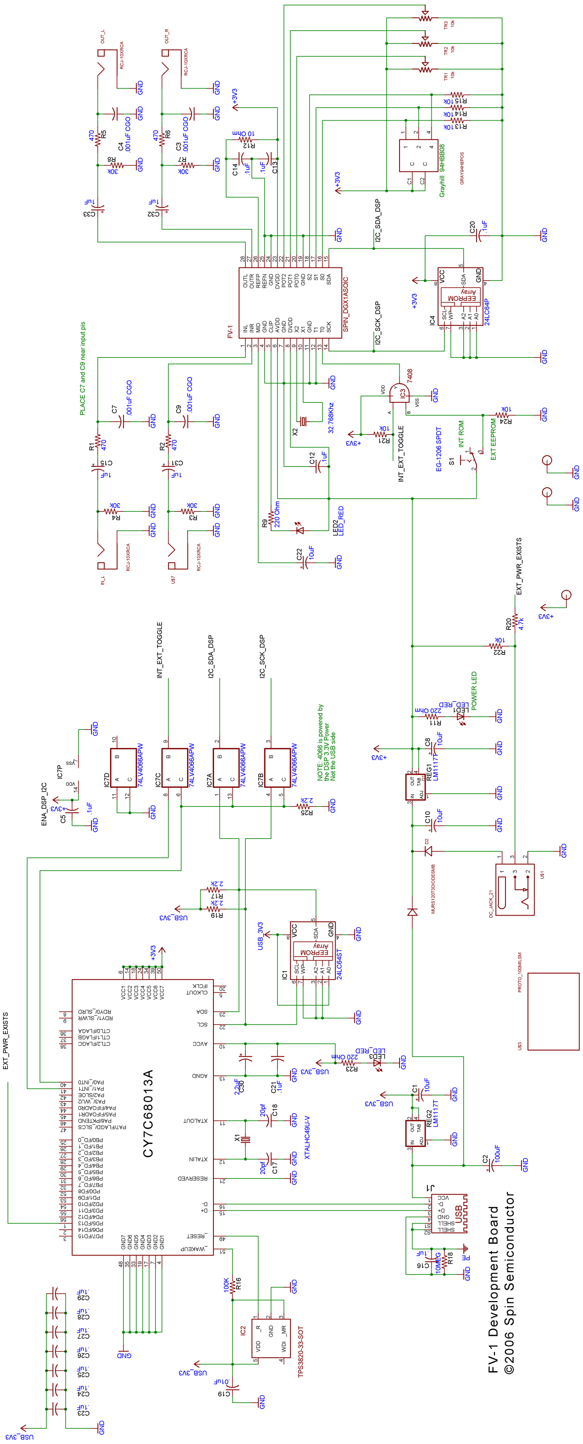


Figure 4.4: SPN1001-DEV schematic[6].

4.2.2 FV-1 Development PCB

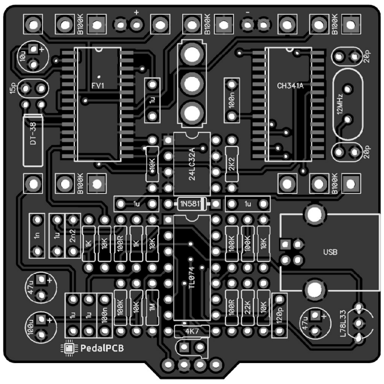


Figure 4.5: FV-1 Development PCB[7].

FV-1 Development PCB is an open-source development board from PedalPCB. This product comes only as PCB with assembly instructions such as component values, schematic so that the customer can assemble it by himself. The advantage of this option is that the PCB costs approximately 300czk [7] plus the price of the components. It has an integrated USB programmer for EEPROM. Program selection is fixed only for the external program options, individual program option is limited for only three program use with SP3T switch, all three potentiometers for the user changing internal parameters, mix potentiometer for dry signal and effect, volume potentiometer, mono input and output with connectors for a user to choose, input/output buffers with chosen values for guitar effect pedal use.

The main advantage of this development kit is that it can be used as a simple but fully functional guitar pedal. Disadvantages are the possibility of choosing any of the internal programs or switching between all eight programs for developing purposes. I chose FV-1 Development PCB from PedalPCB as a test development kit for my project.

4.3 Development kit assembly

I assembled the FV-1 Development PCB with instructions from the PedalPCB and installed it to Hammond 125B enclosure to test its functionalities for my digital guitar pedal, see on 4.7. The controls are on the top row pot0, pot1, pot2, second top row mix control, program select, volume, on the bottom you can see 3PDT footswitch that switches (as true bypass, more about this topic in Bypass switching section 5.2) between bypass and on mode (and turning on LED).

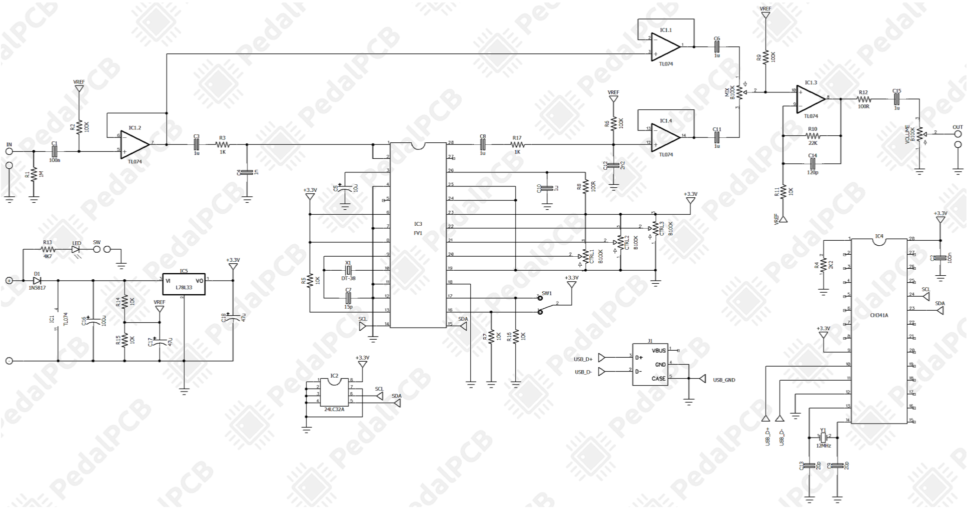
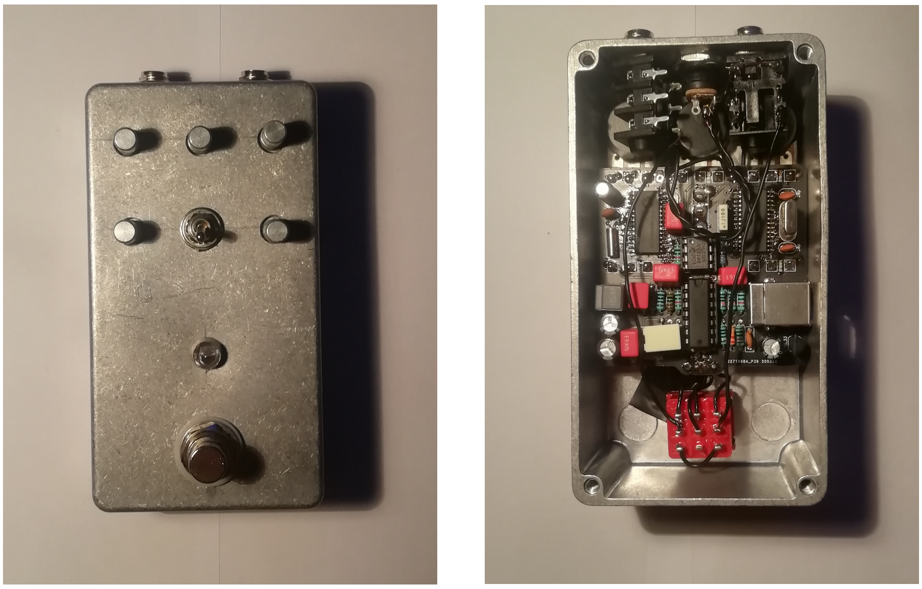


Figure 4.6: FV-1 Development schematic[7].



(a) : Top view.

(b) : Bottom view.

Figure 4.7: Assembled FV-1 Development PCB from PedalPCB.

4.4 First program run

Because the FV-1 Development PCB has fixed the option for running only external programs from the EEPROM, I had to program the external memory to run it. The programming procedure was not as straight forward as it seemed, but I followed the instructions in the FV-1 Development PCB manual, and after trying a few drivers for the CH341A programmer, I succeeded. First, you need to load existing programs in assembler to the SpinAsm IDE project and export it in Intel Hex file. Then convert hex to a binary file, load it to the AsProgrammer, and if the driver for the programmer is installed correctly, choose 24LC32A and write it to the EEPROM. After disconnecting the USB and powering it with an adapter, the programs load in and the pedal starts working.

Chapter 5

Circuit design

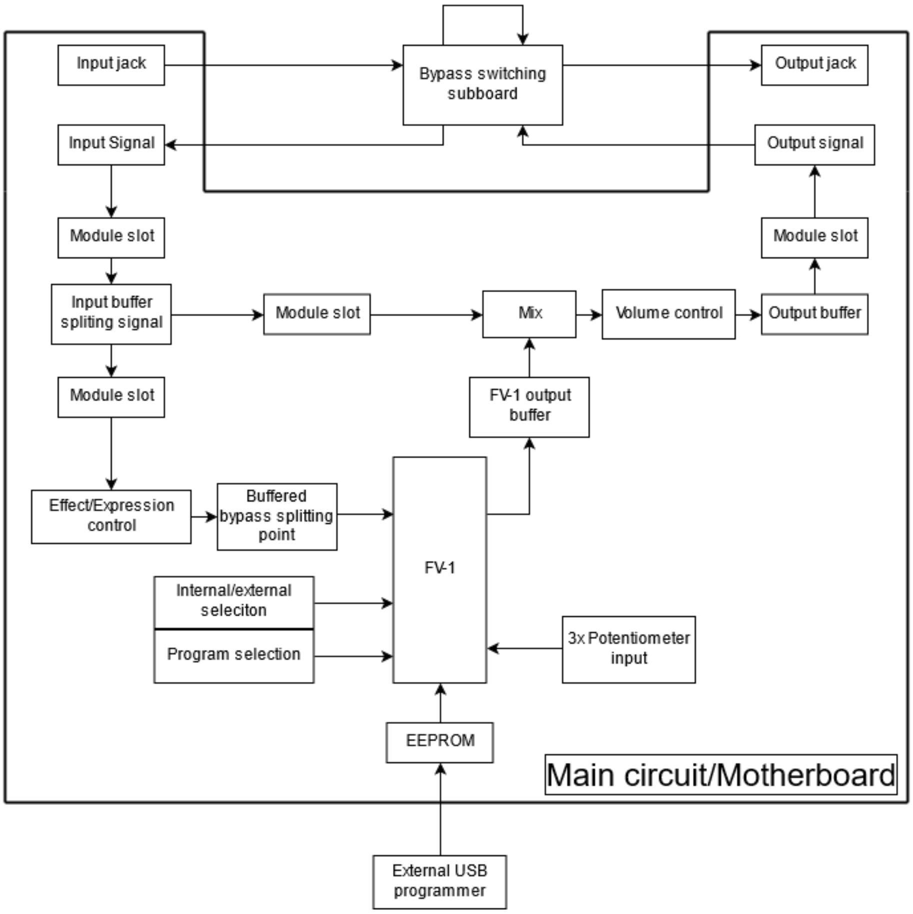


Figure 5.1: Block diagram of the pedal.

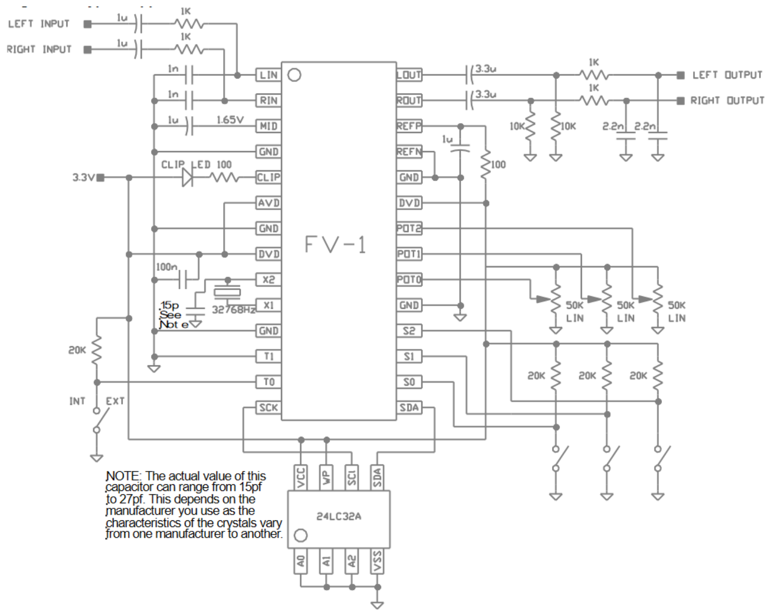
In figure 5.1 you can see the block diagram of the pedal. Module block represents effect module with bypass switching inside, so it is bypassing the signal when off and signal goes through when on.

Circuit schematics of this pedal are direct schematic from which the PCB is drawn. Therefore some components do not have specific functionality other than to serve as jumpers or to fix values (for example, to fix the position of potentiometers).

Resistors that have $0R$ or NP value work as SMD jumpers. This way, it can have much variety of the outcome and still be cheap to assemble in production.

An example for fixing the values is if we would have a reverb effect with three controls: Reverb, HP filter, LP filter. We assume that we have preprogrammed the EEPROM memories and some user wants to fix the HP filter and LP filter in the middle position. We can easily fix it by removing the potentiometer and placing the resistors there.

In FV-1 documentation on page 5 [8] you can find a typical application circuit diagram for integrating FV-1 sound processor into audio devices (see on figure 5.2). It consists of the required clock oscillator for the processor, connection with external EEPROM memory 24LC32A, clipping diode for input overflow, user controls (potentiometers and program selection), which I will include in my design.



NOTE: The actual value of this capacitor can range from 15pf to 27pf. This depends on the manufacturer you use as the characteristics of the crystals vary from one manufacturer to another.

Figure 5.2: Typical FV1 application from documentation[8].

5.1 Main board (motherboard) schematic

Complete schematic is on figure 5.3, 5.4 and in attachments A. For better clearance and understanding I will break down the schematic into sections. You can find partlist for the motherboard for a typical application with true bypass in attachments A.

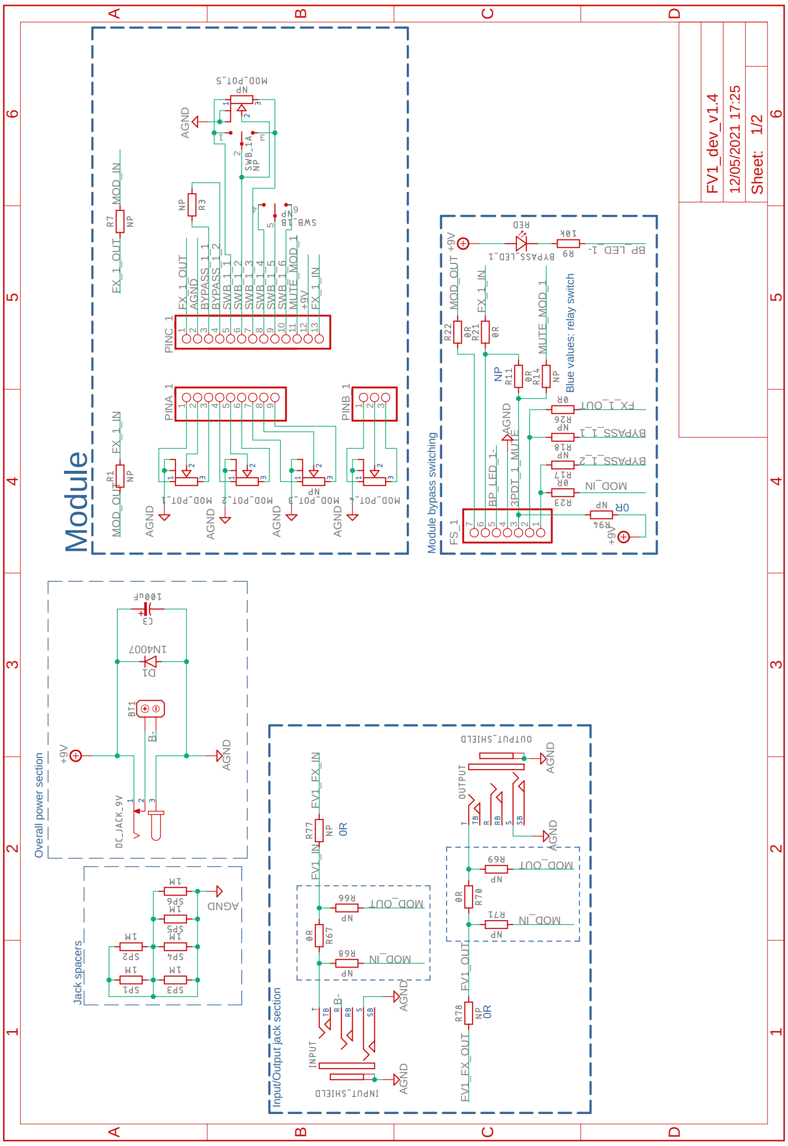


Figure 5.3: Main schematic 1.

5.1.1 Power section

The power section splits into two schematics. First is the overall power section, second is the power section for the FV1 pedal.

In the overall power section 5.5, is the DC jack socket. I chose to use three-pin DC socket where the pin one and three output the DC voltage from the DC

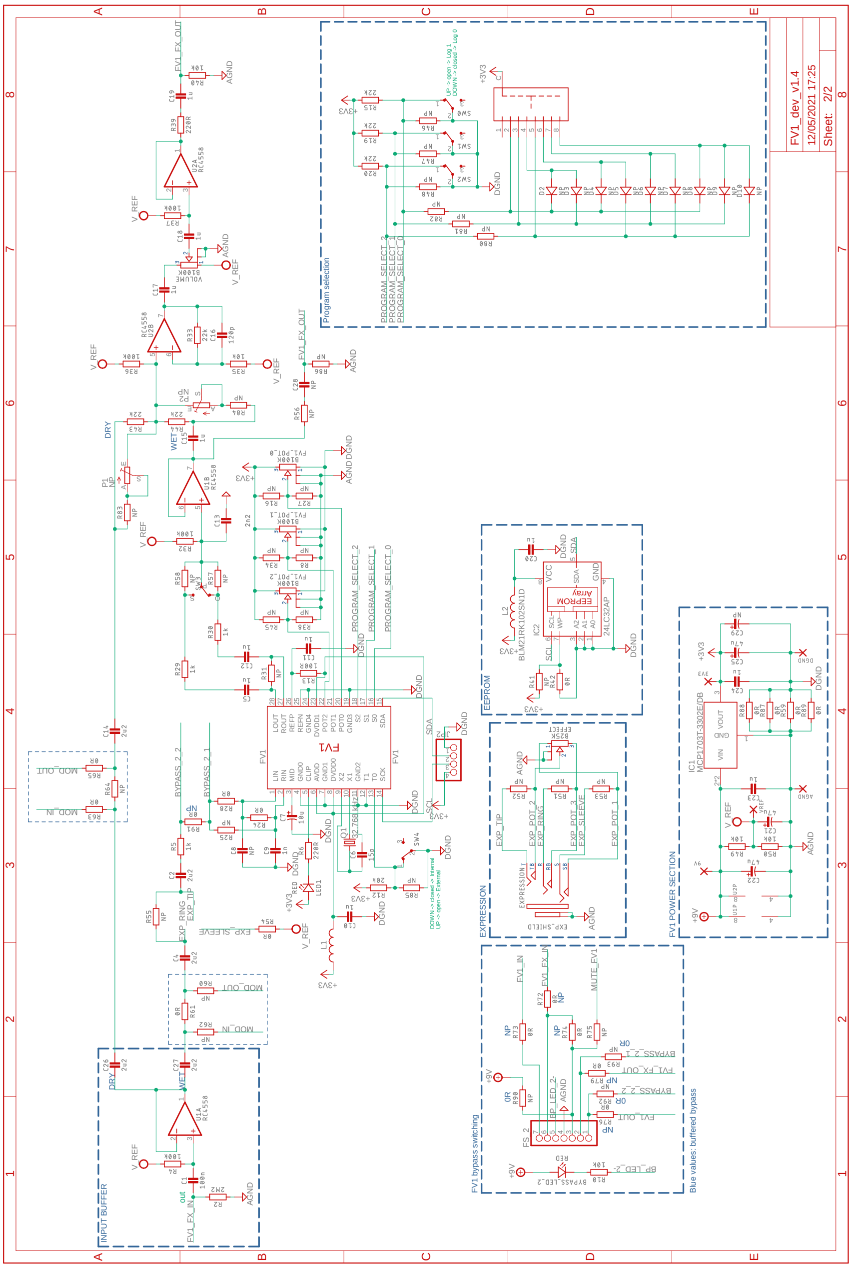


Figure 5.4: Main schematic 2.

jack, and pin two is for the battery plus pole. The three-pin DC socket works so that when the DC jack is not plugged in, the pins one and two connect, and when you plug the DC jack in, pin two disconnects. This way, you can prevent a parallel connection of the DC jack and battery. The minus pole of the battery is connected to the ring of the input jack. When the input cable is not plugged in, it is not connected to the ground, so the battery is not

powering the circuit. When you plug in the cable, since we are using mono cables, the ring and sleeve connect, and since the sleeve is grounded, it will complete the connection to the circuit.
Diode D1 protects the circuit from the reverse voltage on the DC power jack. Possible capacitor C3 helps to filter out noise from the DC adapter.
This solution prevents the parallel connection of the dc power jack and battery, protects the battery from discharging when cables are not plugged in and protects the circuit from a reverse voltage input.

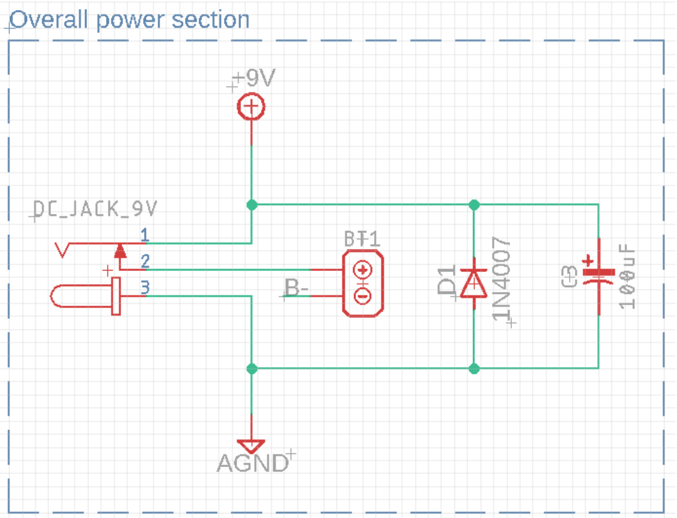


Figure 5.5: Overall power section.

FV-1 power section 8.6 consists of connecting OP amp power pins, R49, R50 and C21 creating virtual ground for the OP amps (to use op-amps with asymmetrical power supply). If we suppose that the power source (DC adapter or battery) is close enough to the ideal voltage supply (with 0Ω output impedance), we can calculate based on Thevenin's theorem the output impedance of the virtual ground as two $10k\Omega$ parallel resistors, which gives us output impedance of $5k\Omega$. The $+3V3$ voltage regulator with capacitors on the input and output to be placed close to the regulator to produce stable $+3V3$ output voltage. I also divided the ground into the analog and digital ground which connect only by resistor jumpers to reduce noise getting from the F-V1 into the rest analog circuit.

5.1.2 Input and output jack section

The overall design thought about the finished pedal is that we have an FV-1 pedal that is complete on one board with the option of the module plugging in some place of the signal path. So if we have the module slot bypassed everywhere, you can see the two net names FV1_IN and FV1_FX_IN,

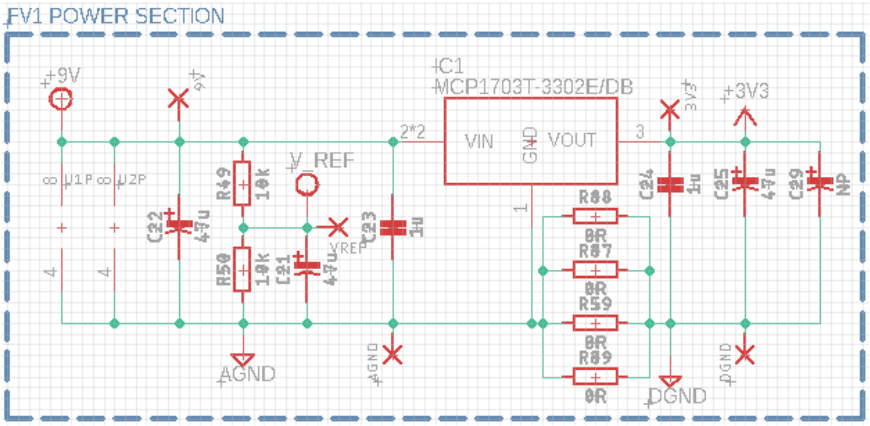


Figure 5.6: FV1 power section.

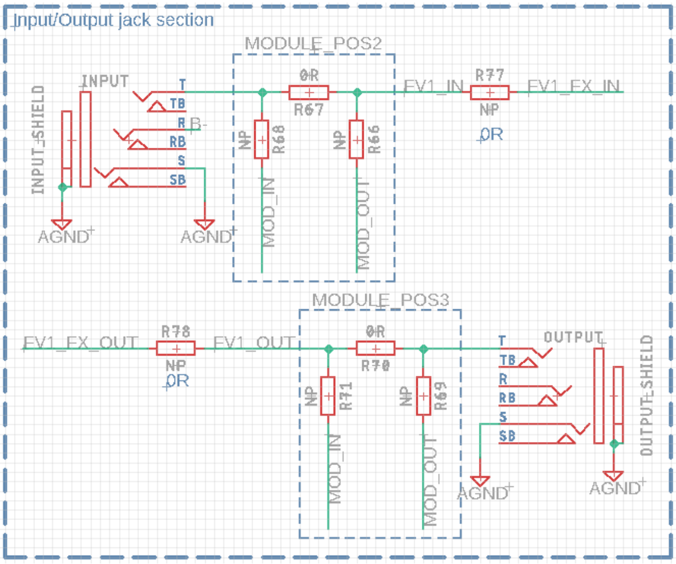


Figure 5.7: Input/Output section.

which are connected by toggling switch for true bypass or can have fixed connection via resistors with 0R value for buffered bypass option. There are effect module slots for series combinations (module before digital effect for MODULE_POS2 and reverse for MODULE_POS3).

5.1.3 Module section

Effect module is a separate PCB that can plug into the pedal motherboard (where the rest of the FV-1 pedal is) and the motherboard has all the electromechanical parts that are necessary to complete the circuit like potentiometers, switches, or overall power supply. It has its separate bypass switching. To

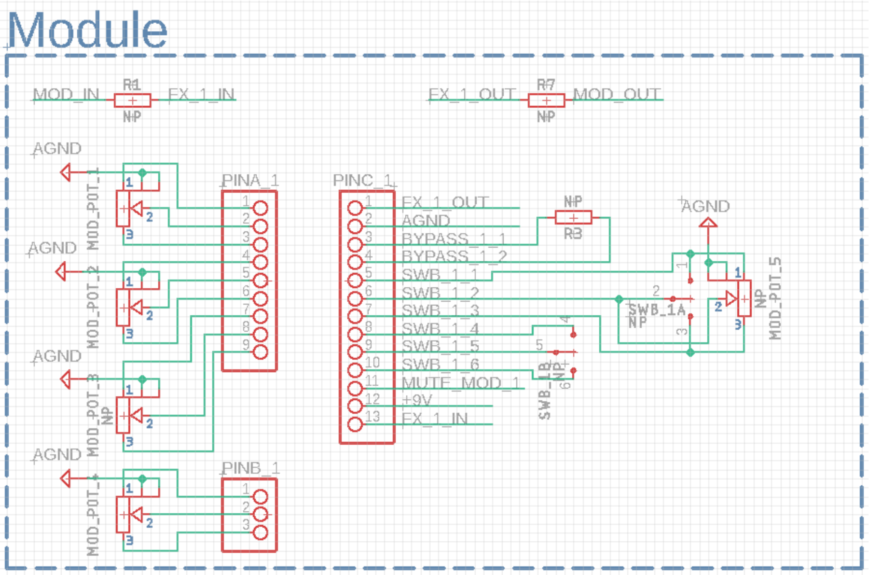
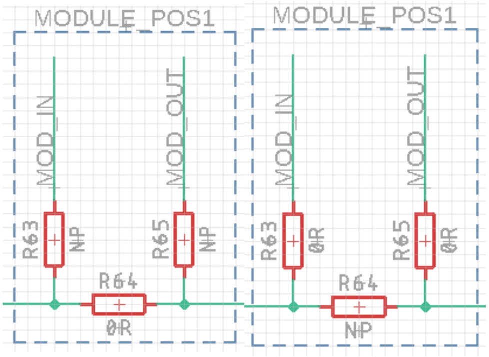


Figure 5.8: Module pinout.

perform as true bypass connect/disconnect MOD_IN net with FX_1_IN and MOD_OUT with FX_1_OUT. To assemble buffered bypass, for example, for some kind of chorus pedal that has dry and wet signal in design, you assemble R1 and R7 as 0Ω, and you operate the turning on and off by connecting/disconnecting BYPASS_1_1 and BYPASS_1_2 for example with JFET, photorelay or mechanical switch. MUTE_MOD_1 pin is for modules that need to be muted somewhere else than on the input to, for example, lower the noise when off.

Where in the signal path you want to place the module is again based on



(a) : Example of resistor values for bypassing the module slot.

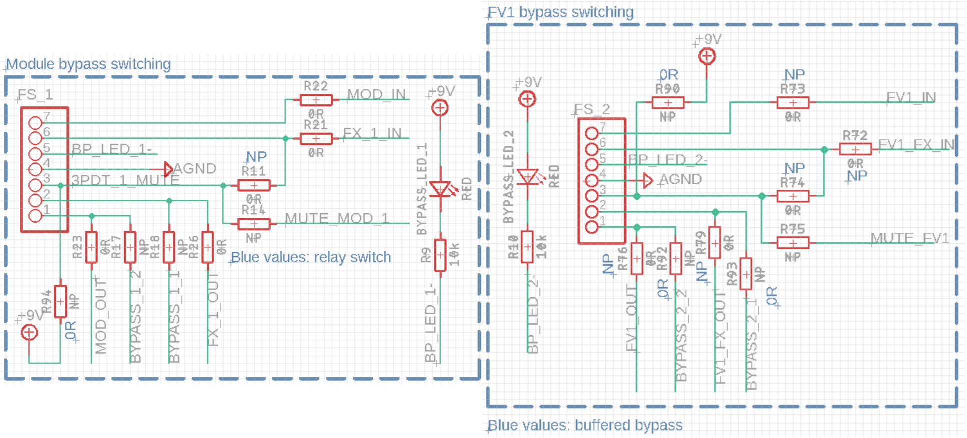
(b) : Example of resistor values for going through the module slot.

Figure 5.9: Resistor values for wiring the effect module into FV-1 pedal.

where resistor jumpers are assembled to make the connection with the FV-1 pedal, see on figure 5.9. This gives a large variety of where the signal can be affected. It can be assembled, for example, as an overdrive module only in the dry signal path, so the delay on the output of FV-1 is clean from the dry signal, and it mixes with the overdriven signal in the output section. See individual possible placements of the effect module in figure 5.3 and 5.4.

5.1.4 Bypass switching sections

Switching will be done on a separate subboard. In the main schematic, there are only pins that connect to the subboard to the specified nets. In these sections, we can see the pinout for the switching subboard. The thought for the design is to have the same pinout for the switching subboard, so it doesn't have to have different subboards for the effect module and FV-1. For the indicator led to light up, you connect pin 5 and pin 4. For the buffered bypass, you connect the nets BYPASS_X_1 and BYPASS_X_2, where X is one for the module switching and two for FV-1 bypass switching.
Traditional buffered bypass switching is done by connecting/disconnecting the signal path before and after the signal processing because the typical application (delay) reproduces any noise from switching. Because usually JFETs are used for disconnecting the signal path, and they have the same power supply as the OP amps in the input buffer, they let the signal through when the input is amplified. Buffered bypass in this project is done by photorelay TLP222g, which ensures noiseless switching and does not let any signal through when in off mode. This way, you can have the sound processor output signal (for example, repeats in delay) fade out on its own. It also needs to connect pin 3 to the $+9V$. This topic is discussed further in section



(a) : Module switching subboard pinout.

(b) : FV-1 switching subboard pinout.

Figure 5.10: Pinout for switching subboards.

5.2.

For true bypass, you connect pin 1 and 7 for bypassing the signal, and for the signal to go through the pedal, you connect pin 1 and 2 and pin 6 and 7. Pin 3 has two functions. When assembling the true bypass subboard, it is not connected to anything when the pedal is on. When the pedal turns off, it connects to the ground and functions as a mute, which can be useful to eliminate noise on the input to be amplified when bypassed. This is useful for the effect modules, and I added it for the FV-1 for debugging purposes. Another way that you can use pin 3 is that for processor-controlled bypass, you need power for the processor so that you can send it to the subboard via pin 3. Resistors are here only to enable the right connections as jumpers. More about how the switching works in the Bypass switching subboard section 5.2.

5.1.5 FV-1 input buffer

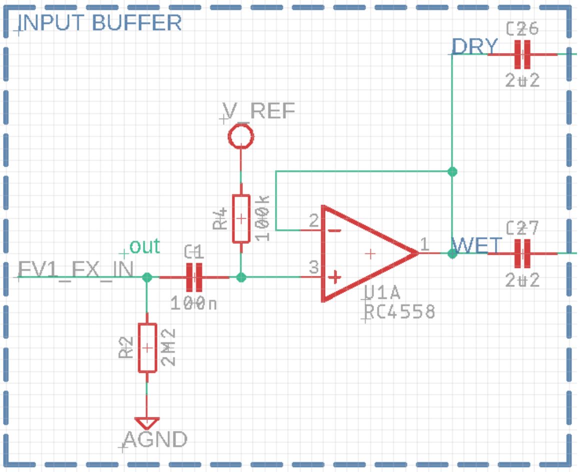


Figure 5.11: Input buffer.

This section has to set the input impedance and split the signal for the effect signal paths dry and wet. Capacitors C1, C26, and C27 serve as coupling capacitors to separate DC voltages from the rest of the circuit. From the voltage follower constructed from OP amp, the signal splits, one way to the FV-1 for processing as wet signal and one to the mix as the dry signal.

The input to the effect is often direct cable from the guitar or another effect, which have commonly low impedance output (at least under $1k\Omega$, usually around 200Ω). To prevent signal loss, the input buffer is set to have large (at least $10k\Omega$) input impedance. Since the OP amp has very large input impedance (over $1M\Omega$), it is neglected from the calculation. The Vref (virtual ground) has output impedance of $R_{Vref} = 5k\Omega$, we add the value with the $R4$ and get $R4^* = R4 + R_{Vref} = 105k\Omega$. For the calculation we neglect the coupling capacitor C1 and calculate the input impedance R_{IN} with Thevenin's theorem as:

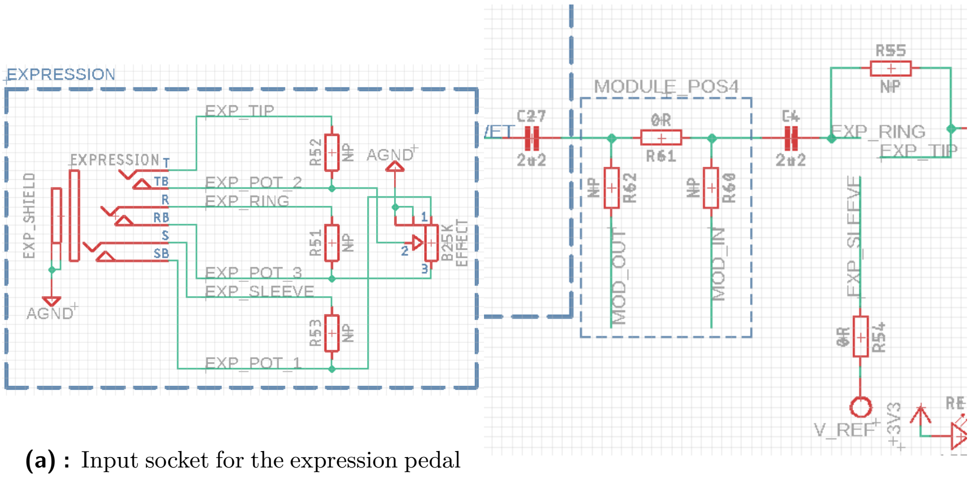
$$R_{IN} = R2||R4^* = \frac{R2 \cdot R4^*}{R2 + R4^*} = 100.22k\Omega \approx 100k\Omega$$

$100k\Omega$ is well over our desired limit of $10k\Omega$ input impedance.

After the input buffer on the wet signal path, we have the expression pedal. It is a basic voltage divider that controls the output voltage signal as volume control. The connections are made by the six-pin stereo jack socket (see on figure 5.12). Three pins (T, R, S) connect to the cable, and three pins (TB, RB, SB) connected to the first three pins when not plugged in and disconnect when the cable is plugged in. With this jack socket, the wiring works so that when the expression pedal is not plugged in, the effect pot is connected and controls the wet path volume. When the expression is plugged in, the effect pot disconnects and the expression controls the signal volume. The expression pedal connects before the signal processing (FV-1) so that when the FV-1 is programmed as delay, it produces an effect close to a controlled reverb pedal by controlling it with an expression that is very useful and is not very common with market delay pedals. To assemble the pedal without expression, assemble the R51, R52 and R53 with 0Ω value. To better understand the expression section, see main schematic 5.4.

5.1.6 FV-1 main effect block

The main effect block of the FV1 effect is based on the schematics from the FV-1 datasheet [8] and an open-source project FV-1 dev PCB from PedalPCB



(a) : Input socket for the expression pedal with effect pot.

(b) : Placement of the expression in the circuit.

Figure 5.12: Expression pedal section.

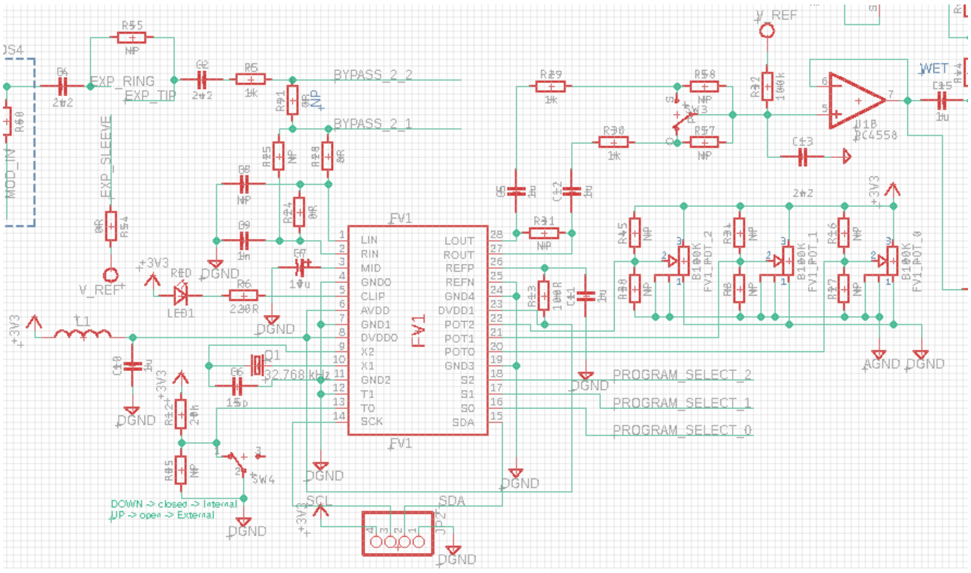


Figure 5.13: FV-1 main effect block.

[7]. Q1 is a basic $32.768kHz$ crystal, LED1 with the current limiting resistor $R6 = 220\Omega$ is a clipping diode to debug if the input signal is overflowing the input. The FV-1 is $+3V3$ powered processor, and the incoming signal from a different amplifying pedal will probably be peak-to-peak $+9V$. In that case, you can observe the clipping led and then reduce the incoming signal with a $R61$ resistor, which creates a voltage divider with the effect potentiometer. I have added resistors for the possibility of fixing the potentiometers and switch positions. There is an inductor L1 (BLM21RK102SN1D) between the $+3V3$ and the DC power input of the FV-1 DVDD and added a $C10 = 1\mu F$ between the power pin and ground to help with power stabilization. Another essential feature is that there is a switch SW4 to select the location of the program (internal ROM of the FV-1 with pre-programmed programs or external EEPROM). Since the FV-1 is designed for usage in stereo devices, there is left and right input and output. For the input, there are resistor jumpers to add the choice of sending signal into left or right input, but it will be probably fixed with the resistors values as seen in figure 5.13 to send the input to both left and right inputs. It is possible to write a FV-1 program that produces different signals on left and right outputs. The reason why it would be required for some design when we have program selection is that the program selection restarts the FV-1 chip and its memory, so it forgets the recorded sound, for example, in the delay pedal. For this reason, there is a possible SW3 to switch between left and right output signals. Voltage follower after the output is there to avoid FV-1 output affecting the mix section. Voltage follower sets the output impedance low enough that it does not influence the mix section. There are components after the voltage follower for a straight output skipping the mix and output buffer section for versions of the pedal which do not require dry signal (for example, digital parametric EQ).

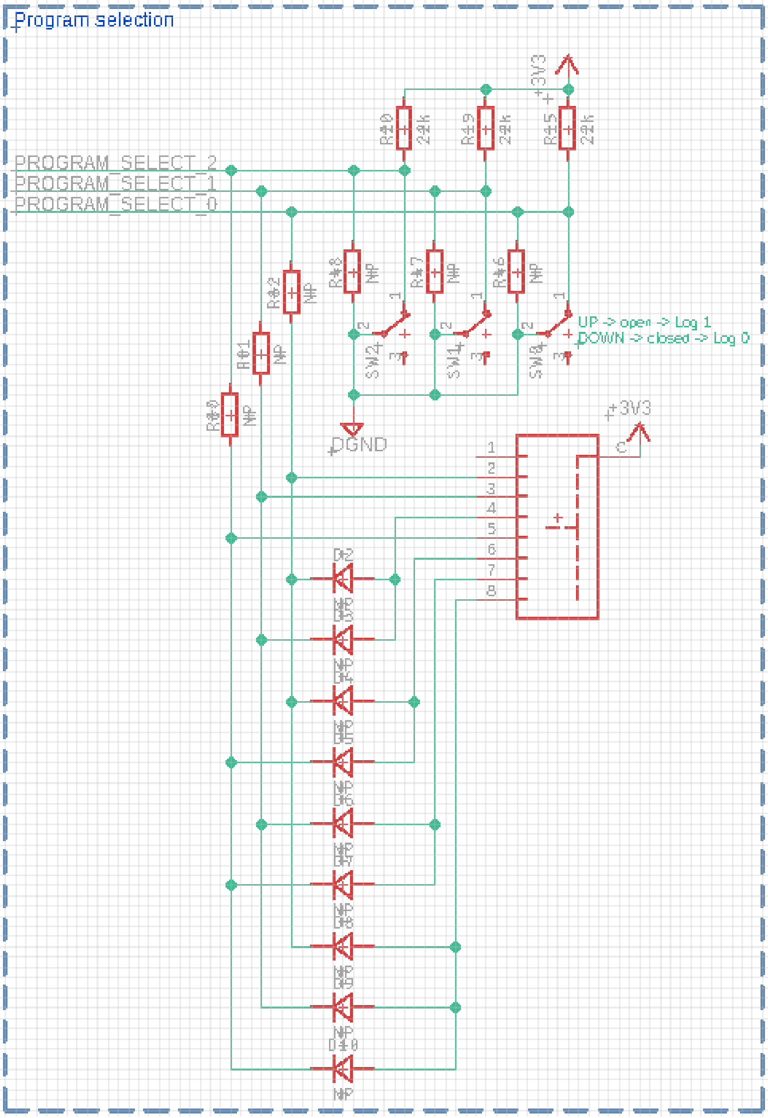


Figure 5.14: Program selection section.

Program selection works as a standard 3-bit number input (eight positions, eight programs), LSB on 16th pin S0 and MSB on the 18th pin S2 with $+3V3$ as logical one and $0V$ as logical zero. For this design, there are two ways to make the program selection. First is the 3 independent switches SW0, SW1 and SW2 5.14. This method is suitable for modifications; for example, if we want to do a pedal with only two different programs, we can assemble a version with only one leaver, and the other we can fix with 0Ω/NP resistors. The disadvantage is that if we do eight different programs multipedal, the leavers are complicated to operate. For this purpose, there is a 1p8t rotary switch 5.14 which can select the program by its position. Diodes prevent positions wiring from influencing each other 5.14. FV-1 loads external programs from 24LC32A EEPROM (recommended in FV-1 dev

PCB from PedalPCB [8] and from FV-1 datasheet [7]). The resistors R41 and R42 are to set if the memory is readable/writeable by setting the WP pin low for programming and high for disabling programming memory. If the resistor is assembled R41 as 0Ω and unassembled the R42, the memory is reprogrammable. If R42 is assembled as 0Ω and R41 unassembled, the memory is reprogrammable to avoid copying programs 5.15.

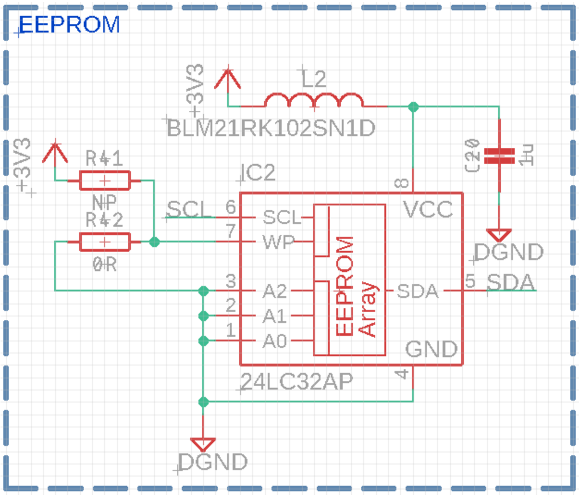


Figure 5.15: EEPROM circuit.

5.1.7 Mix of the dry and wet signal

Mix section is based on the mix from PedalPCB [7]. The mix is set by either resistor R43 and R44 or by assembling trimmers P1 and P2 with resistors R83 and R84 to have it adjustable 5.16.

5.1.8 Output buffer

Output buffer includes the volume control, and its purpose is to set the output impedance low and to make up for the high impedance output of the volume control potentiometer.

Volume control works as a simple voltage divider. The goal of the output impedance is to have it at least under 500Ω but higher than 100Ω. The impedance is lowered by the OP amp voltage follower and then set by the R39 and R40 resistors. We can approximately calculate the output impedance with Thevenin's theorem. We neglect the coupling capacitor, which blocks

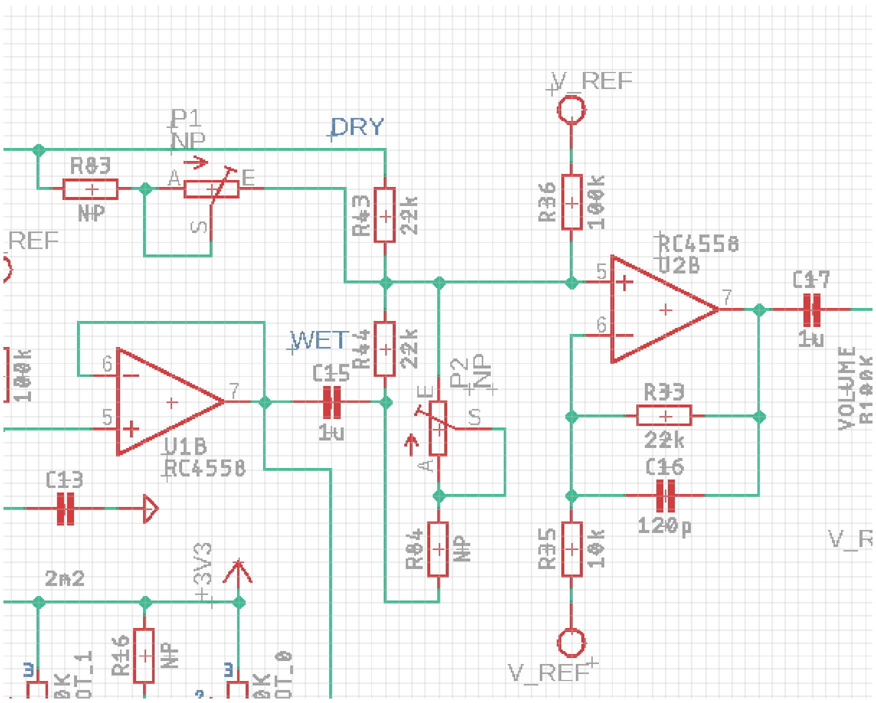


Figure 5.16: Mix section.

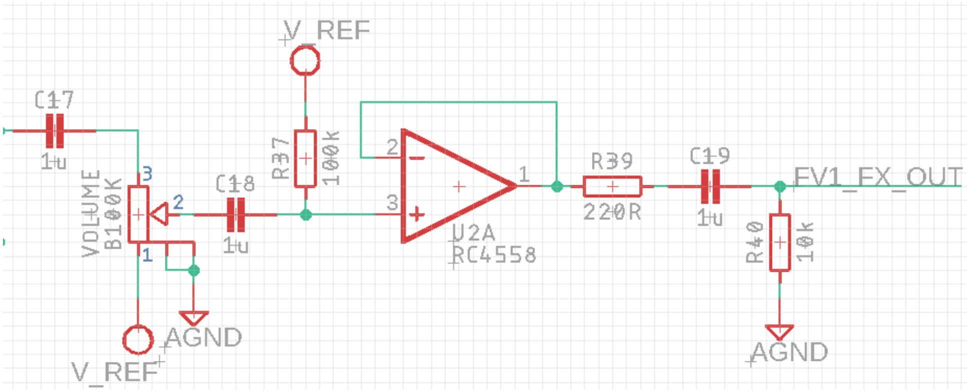


Figure 5.17: Output buffer.

the DC voltage from the output, and the OP amp's impedance since it will be significantly lower than the overall output impedance. That said, we calculate output impedance as:

$$R_{OUT} = R39||R40 = \frac{R39 \cdot R40}{R39 + R40} = 215.26\Omega \approx 200\Omega$$

Output impedance is set not as low as possible but to around 200Ω because it can have benefits for some pedal combinations (for example, to lower pop sound of the mechanical switch by effectively muting the output by photorelay with on-state resistance of about 30Ω).

5.2 Separate bypass switching sections

For the pedal to have different bypass switching options, the switching circuit is placed on a separate PCB from the main board. These connect to the main board by pin row or by ribbon cables. The pinout for the row of pins is the same for the effect module and FV-1, so the switching subboards do not have to be designed separately. To see how the pinout works, see section 5.1.4.

5.2.1 True bypass switching

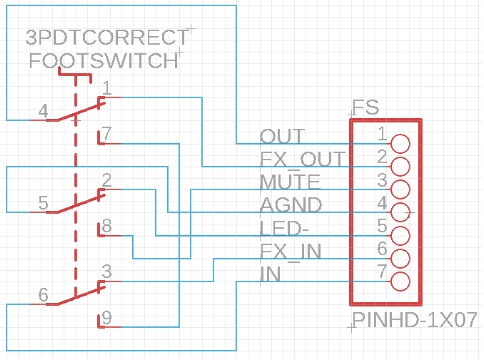


Figure 5.18: True bypass subboard.

True bypass works by 3PDT footswitch 6.4. The first switch connects pins 1 and 2, and the third connects pins 6 and 7 when in on state. When switched to the off state, the footswitch connects the pins one and Seven directly to create a true bypass. The second switch connects pin 4 and 5 to light up indication led. The other pin of the second switch mutes pin 3. It connects to the ground when off (see 5.2) and stays disconnected when on.
True bypass has the advantage of not influencing the signal when off, and it can let the signal through when off and unpowered. The main disadvantage is that the mechanical switch produces pop noise on the output when toggled.

5.2.2 Buffered bypass switching

Buffered bypass is done by connecting pin 1 and 2 when turned on and disconnecting when turned off. For simple buffered bypass switching, I chose 3PDT footswitch 6.4 like in a true bypass that connects pin 4 and 5 to turn on indication led, but it does not connect pin 1 and 2 directly for bypass

because the way the FV-1 pedal is designed would produce pop noise that would the delay repeat (for more info see 5.1.4). There are many ways that for connecting and enabling pedals in buffered bypass.
The first possibility is connecting directly by a mechanical switch that is not very good since, as said before, it produces pop noise which will repeat at the output.

Second, for most pedals, the typical possibility is switching it with a JFET;

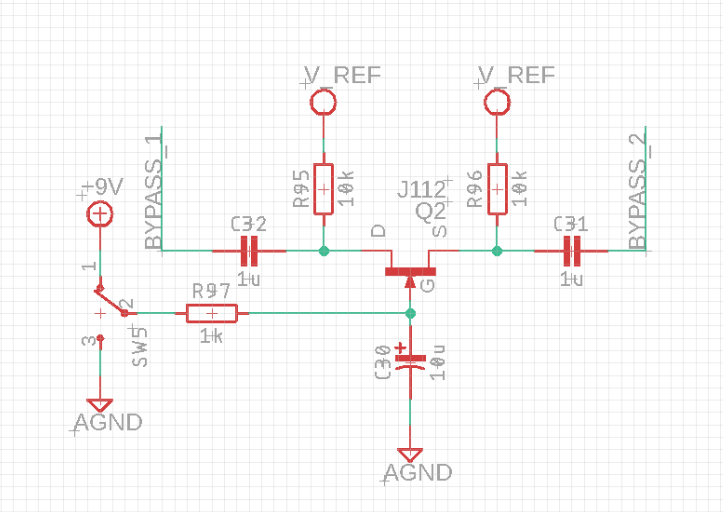


Figure 5.19: JFET switching example.

see a typical example on figure 5.19. The JFET will produce a pop sound too, but if the gate voltage impulse is slowed down by charging and discharging capacitor, it becomes silent. Nevertheless, for this application of buffered bypass has a significant disadvantage. Since the switching of JFET is set by the difference between the gate and drain voltage, when turned off, we have ground on gate and signal on drain voltage (on the virtual ground approximately $+4V5$). When there is some amplified signal (by some booster pedal, for example) on the JFET section it switches the JFET on shortly when the peak of the signal clips the power section of the input buffer (has a value close to the ground) because the voltage difference between drain and gate gets close to zero. Since it is a delay, it repeats the short signal, and it is audible. This problem solves a charge pump creating negative voltage for the gate, but this solution includes many components, which is more expensive and takes much space on the board. For this reason JFET as a switch for the buffered bypass is unusable for our device.

The third option that was designed for this pedal is switching buffered bypass with photorelay TLP222g. Photorelay has on the output large enough resistance to not let any signal through when off and around 30Ω resistance when turned on (see datasheet [29]). Since the signal path and the triggering led are separated; they do not influence each other, it does not produce a pop sound when toggled, which solves the buffered bypass switching. The circuit for the switching subboard with TLP222g is on figure 5.20. Based on datasheet [29] the photorelay trigger current $I_{trigger}$ should be under the maximum rating of $I_x = 3mA$ and the typical trigger current is $1mA$ but the on-state resistance gets lower with a higher trigger current. I chose to trigger it by $I_{trigger} = 1.5mA$. Assuming approximately $0.7V$ voltage drop over the diode, the current limiting resistor R6 is:

$$R6 = \frac{9 - 0.7}{0.002}\Omega = 5533\Omega \approx 5.6k\Omega$$

There are parts for slowing the voltage over the photorelay led for debugging purposes, but it was unnecessary to assemble. Basic assembling for working buffered bypass is shown in figure 5.20. Diode D1 protects photorelay from the reverse voltage because the TLP222g gets damaged when reverse voltage exceeds 5V. There is one switch in the 3PDT switch unused, but 3PDT is more common and cheaper than DPDT or SPDT footswitch, so it is designed with 3PDT.

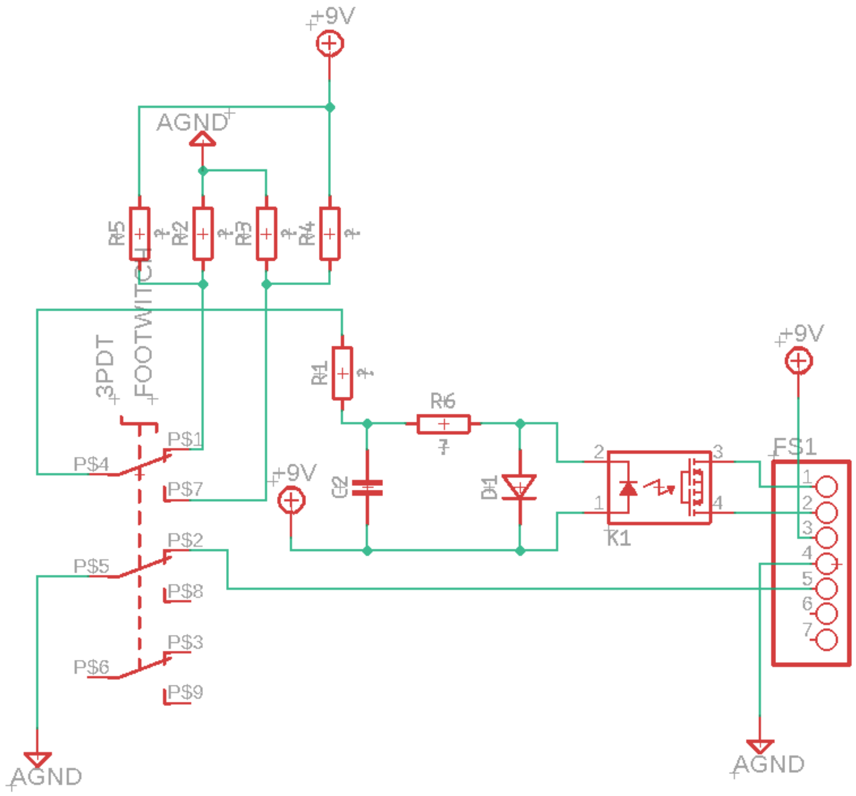


Figure 5.20: Photorelay switching.

5.2.3 Processor controlled switching

It was required to have one more bypass switching option, the controlled relay switching as a true bypass switching alternative and controlled photorelay switching as a buffered bypass switching alternative.

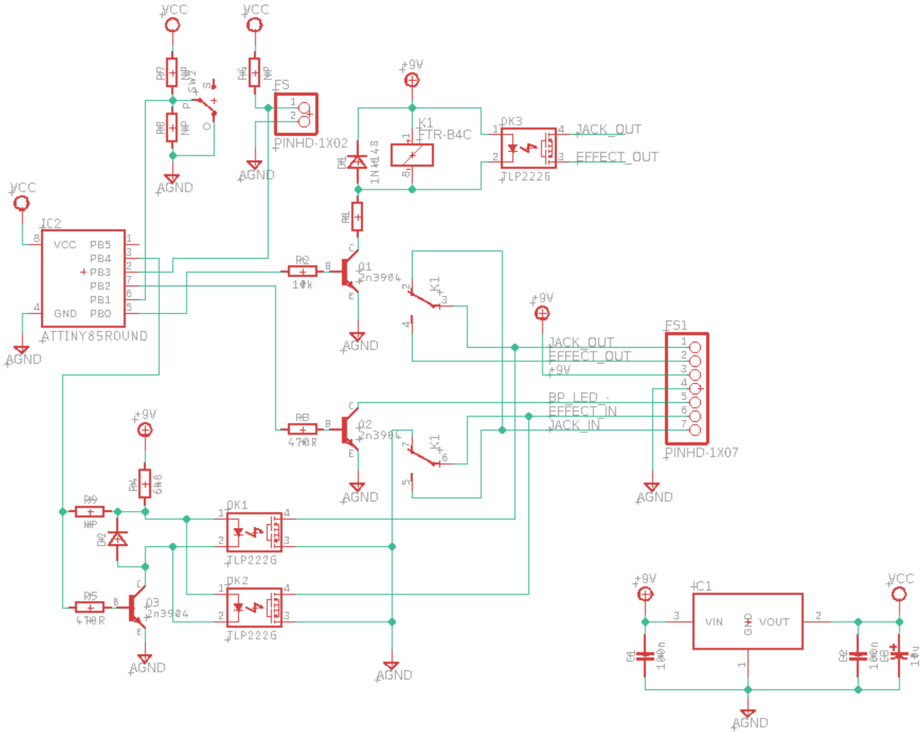


Figure 5.21: Attiny controlled switching subboard.

Relay switching is a great alternative for 3PDT true bypass switching because it creates a physical connection that does not affect the sound. Using processor-controlled bypass switching adds an excellent feature that reduces pop noise sound on the output by muting it with photorelay. The component selection and program are based on an open-source project Relay bypass from Mark A. Stratman [30]. The controlling processor is the Atttiny85 processor that can be programmed using Arduino UNO as a programmer (more about in section Attiny programmer shield for Arduino UNO 7.2). You can find the Attiny85 program for the relay switching in the attachments A.
Attiny processor can be powered by $+3V3$ or $+5V$ power supply. This project includes the 5V power regulator as a power source for the Attiny85.
There are two main options for the relay selection - latching and non-latching. Latching has the advantage of being more power-effective. However, it has the disadvantage of taking one more pin of the Attiny, which is very limited on the number of input/output pins. Non-latching option is constantly draining power when in on position but has a significant advantage of being bypassed

whenever unpowered. Which is something that could be very practical when used in pedalboards. The latching option would stay in the position that it was in when unpowered. We decided to use 5V non-latching version FTR-B4C. Since it is a non-latching relay with a coil inside, it needs some way to discharge accumulated current, so there is D1 anti-parallel with the relay trigger coil.
Relays are usually producing a powerful pop sound when triggered, so there is an OK1 photorelay TLP222g to mute the output before the relay triggers, and after the relay switches the position, the output unmutes after 35ms. The relay toggle is delayed for 20ms after the muting starts to make sure the output is muted already. Since the signal is muted only for 35ms it is inaudible and unnoticeable. There is also a switch for possible user setting input, for example, to enable/disable muting. Since the relay switching can be used for a delay, there is a place for muting (OK2 - TLP222g) the input too, so if the pop sound produces on the input, it does not repeat when turned back on. A transistor controlled by Attiny enables relay and photorelays to avoid overloading Attiny outputs. The user input is momentary switch 6.4 that connects to the ground with an internal pullup resistor.
Since the switching is controlled by Attiny, it can have additional features like writing down the switching status to internal EEPROM, so the pedal stays switched the same when unpowered and powered back. Another additional the feature is that the processor detects for how long you have pressed the button, so when you push it for a short time (less than 350ms), the processor switches the on/off status, but if you hold it for a longer time (more than 350ms), it enables/disables the effect for the length of the button push (it behaves as a momentary switch), which can be interesting for some uses. The main advantage of the relay switching, however, is the physical package. Since the component itself is disconnected from the user input (footswitch/momentary switch), the relay can be placed close to the input jack socket. Having to set the input signal path physically on the board to go from input on the top of the pedal to the bottom of the pedal (which is preferred see the requirements section Controls and input/output layout 3.1.8) can often cause oscillations when building a high gain effect pedal. In this prototype, the relay is placed on a separate board, but for future development, it is required to place the relay onto the main board.
For buffered bypass, there is a photorelay (OK3 - TLP222g) that can be assembled instead of a relay to enable signal passing through the buffered bypass pins 1 and 2. Since the photorelay does not produce any pop sound, it does not have to have any muting, and since it is parallel with the photorelay it does not need to have a different operating program, and the only difference for the assembly, the setting is to change the current limiting resistor R1 from 0Ω to $5.6k\Omega$ based on the calculation above (5.2.2).

Chapter 6

PCB design

The digital guitar pedal consists of several separate PCBs so that they can meet the requirements of all features like different switching options and physical dimensions for fitting into the 1590BB enclosure (more in chapter Guitar effect pedal requirements 3). Example of fully working pedal would be fully assembled motherboard, one fully assembled for example, overdrive effect module and two assembled switching subboards, and for example controlled buffered bypass switching for the FV-1 and controlled true bypass alternative (relay switching subboard) for the effect module part.

To lower the possible manufacturing cost, most of the components are SMD. Resistors and MLCC capacitors are in 0805 packages because it has the advantage of being SMD which is cheaper for production but still big enough to be easily assembled by hand. Dimensions of the PCBs are set to fit into the 1590BB enclosure.

For PCB design, there are some basic rules that are followed throughout the design process. Generally, for PCB design of audio devices, it should always have the input signal path as far as possible from a very amplified signal because it can create noise or even create oscillations. For all of the PCBs I try to place most of the SMD components on one side of the PCB and leave a small number of different components on the other side (for example, on the motherboard). The reason for it is to reduce the manufacturing price. The automatic soldering needs to be done on each side separately, and since the the most expensive part of the process is most of the time programming the automatic staffing robot, it can reduce the cost of the assembling by having only few component types and values on the other side (for example, 0Ω resistors/jumpers, 1N4148 diodes, spacers, and two electrolytic capacitors like on the motherboard).

6.1 Motherboard (main board) PCB with the FV-1 effect

The motherboard is the PCB that has the digital effect main circuit on (see main circuit schematic in 5.1), connects all circuits on separate subboards (switching subboards and effect module), and has all electromechanical controls (leavers, potentiometers), pedal input, expression input, pedal output, and indication LEDs. The layout of the controls was set to meet the requirements from 3.1.8.

It is a four-layer PCB with middle layers primarily used to pour copper with ground connected to all pours on the first, third, and fourth layers. Pours help with eliminating the noise that could interfere with the signal paths and they reduce the number of manually drawn copper signal paths. The digital ground of FV-1 is separated from the analog ground of the rest of the circuit and then connected with jumpers (more in chapter 5). They are physically separated on the PCB too, left in the FV-1 part of the pedal there is on layer one and four poured digital ground, and the rest is of the PCB round pour is analog ground. The pour on the second layer connects to the positive pole of the power supply. The positive pole of the power supply means for the FV-1 section $+3V3$ and $+9V$ for the rest of the pedal (so they are separated, left $+3V3$ for the FV-1 digital guitar pedal and $+9V$ for

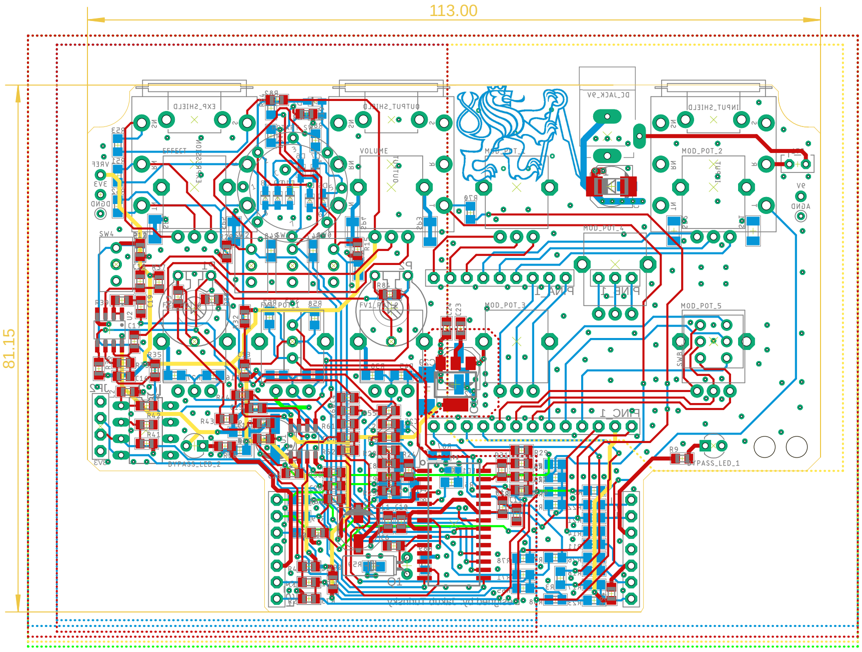


Figure 6.1: All layers of the designed motherboard, dimension measurements in milimeters.

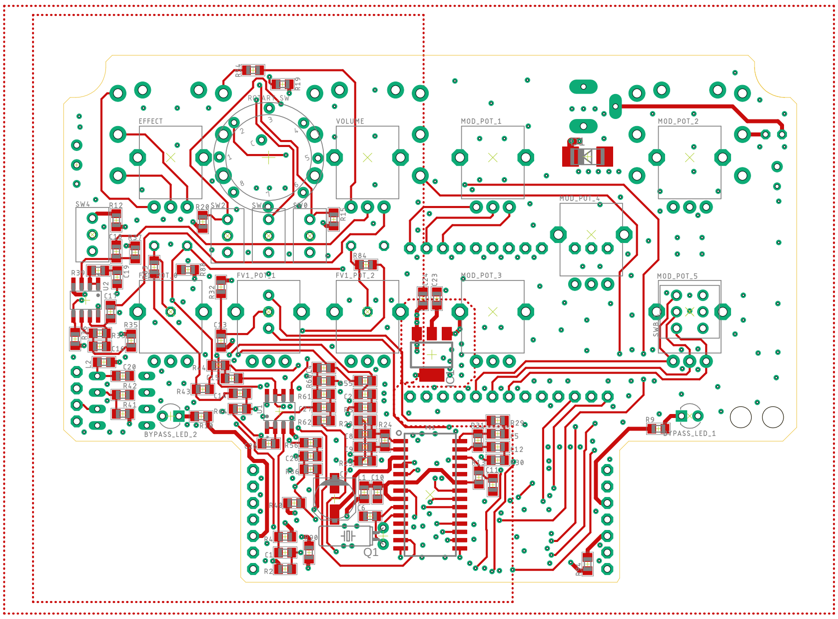


Figure 6.2: Top layer of the designed motherboard PCB.

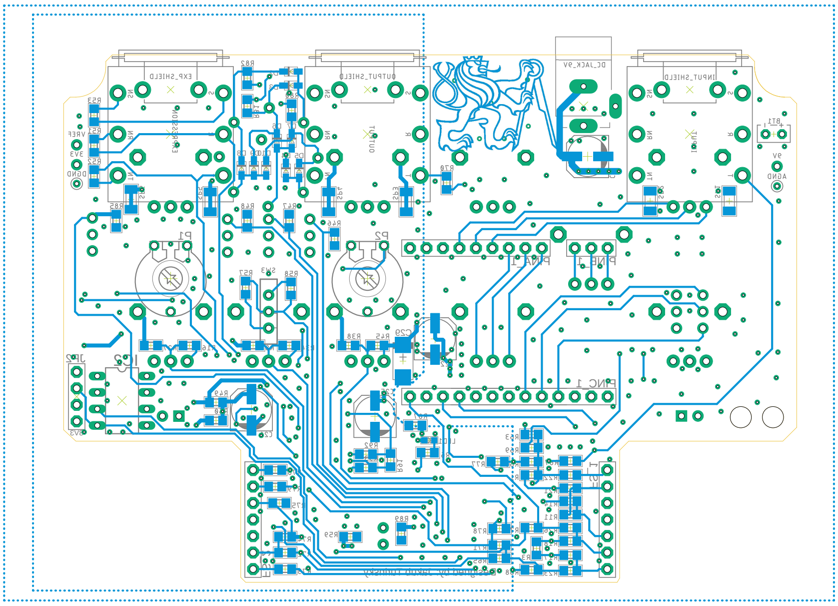
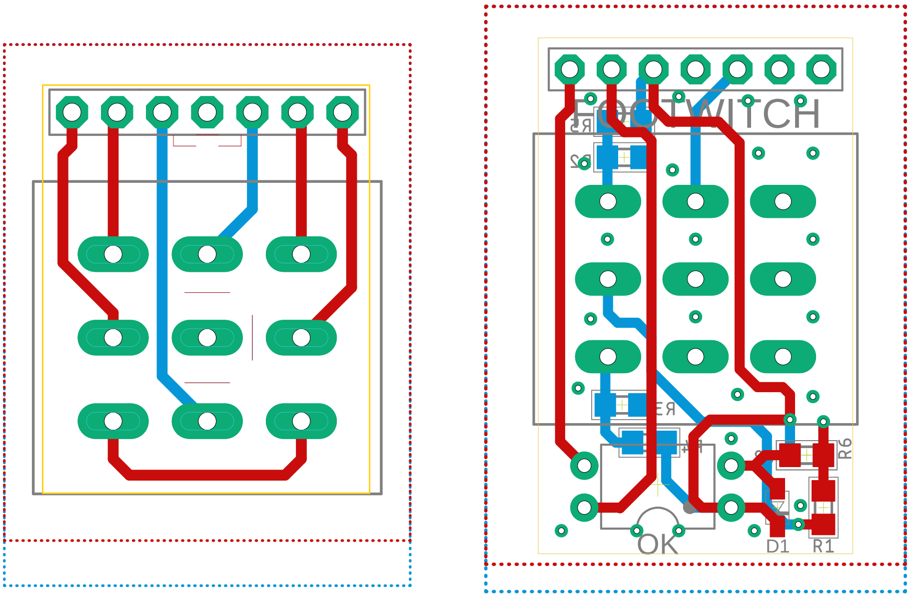


Figure 6.3: Bottom layer of the designed motherboard PCB.

the right part of the PCB). These pours are separated mainly to lower the number of manually drawn copper paths. All of the pours are set to minimal signal path width $12mils \doteq 0.3mm$ and with thermal isolations on. Another specific feature is spacers SP1-SP6 that are 1206 package with not precisely determined type. These components are placed by the automatic assembly line under the 6.3mm jack sockets to angle them and help align them to the concave 1590BB enclosure sides.

6.2 Switching subboards

There are three different switching subboards constructed for the different switching options. True bypass and buffered bypass switching subboards are two-layer PCBs, and processor-controlled switching subboard is a four-layer subboard with same inner layer configuration as motherboard (see above 6.1).



(a) : True bypass PCB.

(b) : Buffered bypass PCB.

Figure 6.4: Switching subboards.

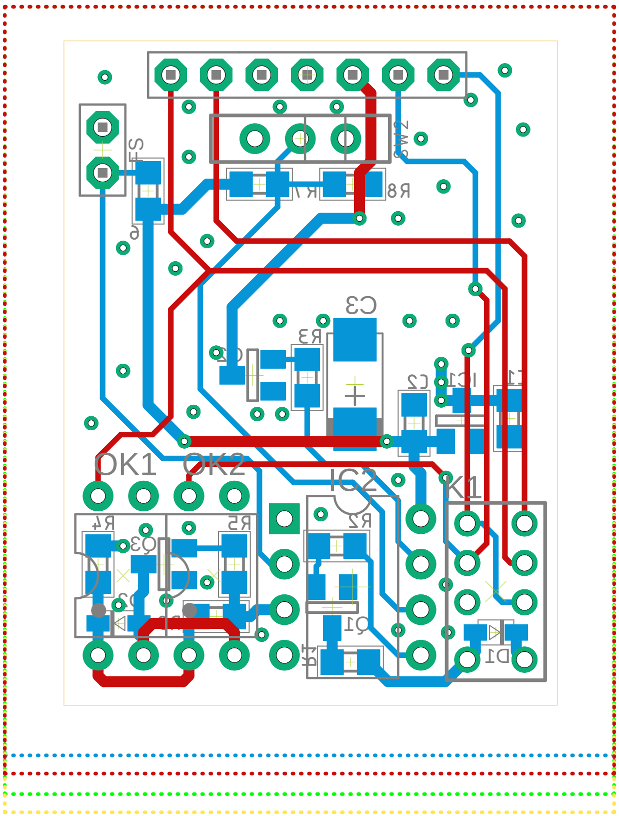


Figure 6.5: Processor controlled switching PCB.

6.3 Enclosure layout drawing

The enclosure drawing is on figure 6.6 (or in attachment A). The holes have diameters:

Hole type	Diameter [mm]
Footswitch	12
6.3mm jack socket	12
Leavers	4.5
Potentiometers	8

Table 6.1: Pedal power usage measurements.

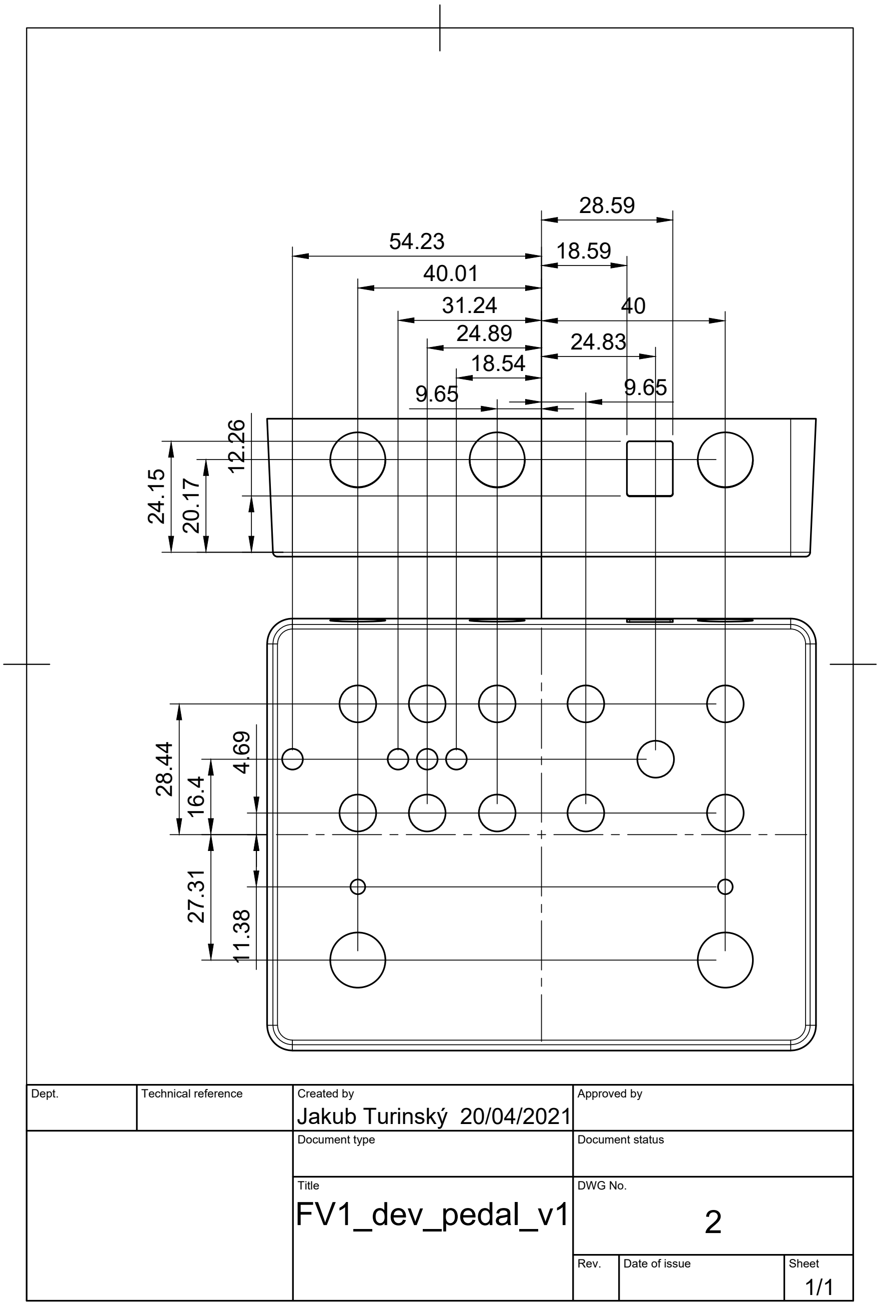


Figure 6.6: Enclosure drawing with measurements.

Chapter 7

Additional custom hardware for running the pedal

7.1 USB EEPROM programmer

FV-1 loads its programs from external EEPROM 24LC32A. Due to covid complications with shipping, I could not get a standard programmer for this unit, so I designed a custom one with PCB based on CH341A programmer chip schematic from PedalPCB FV1 development PCB see in [7]. I added

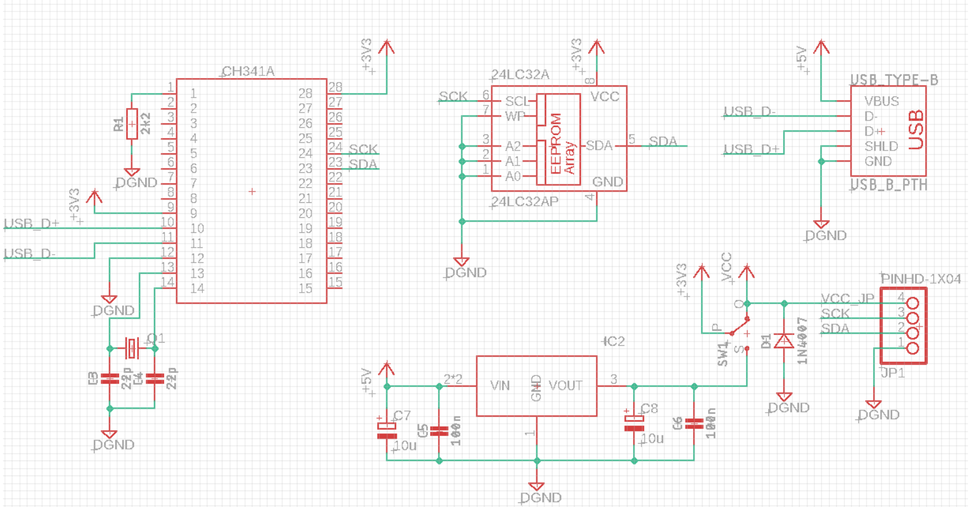


Figure 7.1: USB programmer schematic.

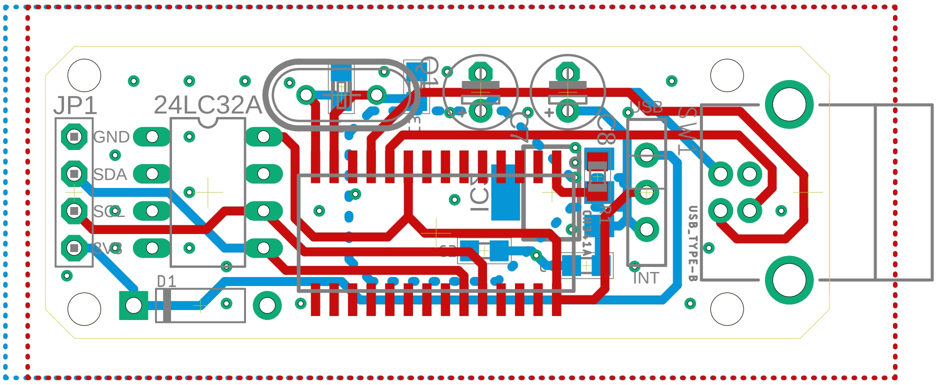


Figure 7.2: USB programmer PCB.

a key feature that will simplify future manufacturing. For the memory 24LC32A, there is THT and SMD option. SMD memory on its own is not ideal for manufacturing because it has to be programmed and then placed back into the rail for automatic soldering. THT can be programmed and then soldered by hand into the main board directly or placed into a socket. It is ideal for testing the pedal working before finishing. If the EEPROM is not programmed correctly before direct soldering, it is untestable for a few hundred pieces. Placing memory into a socket has the disadvantage of being removable. Removable memory can be read and copied, and since the development board is designed to be used as a possible commercial product, it is unwanted. It needs four signal pins for programming the memory: $+3V3$ and GND for power, and SDA and SCL for transporting data. The pins lead aside from the motherboard and included pins with the same pinout on the custom EEPROM programmer. This way, it can automatically solder SMD memory onto the motherboard and program it via a custom external programmer with some ribbon cable connect and program them. In the prototype of the pedal unit, there is THT memory with the pins for testing, but if it will be established that it is reliable enough for manufacturing, the memory can replace an SMD alternative, and when programmed, R41 can be placed as a jumper, which disables reading the memory (more about this topic in 5.1.6). The custom EEPROM programmer has a possibility of being powered by these pins or via USB and diode reverse polarity protection for the power from the pins to prevent damaging pedal/programmer when the programmer is connected via ribbon cable opposite.

7.2 Attiny programmer shield for Arduino UNO

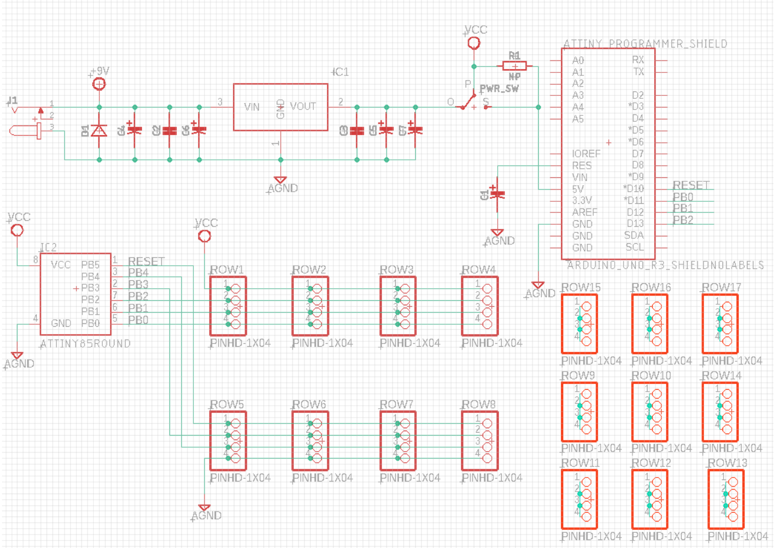


Figure 7.3: Schematic of Attiny programmer shield for Arduino UNO.

Attiny85 processor controls the relay switching, which is programmable with Arduino UNO. To make programming more reliable and easier, I designed a shield for programming Attiny processors with Arduino UNO based on a project from Arduino Project hub [31]. Because there is much space on the PCB, there are pin rows added named ROW9-ROW17 for debugging and testing. For testing programs on Attiny85 externally, I added an adapter socket with $+5V$ regulator (assuming 9V dc jack with a positive pole on middle shaft).

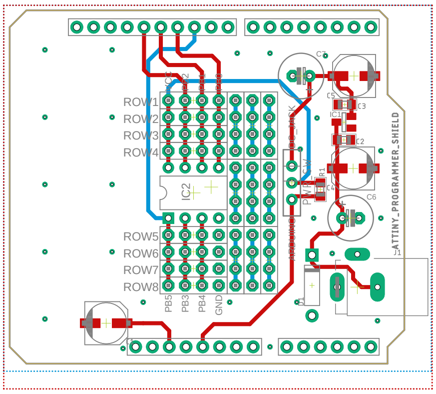


Figure 7.4: PCB of Attiny programmer shield for Arduino UNO.

7.3 Debugging support shield for LEO oscilloscope

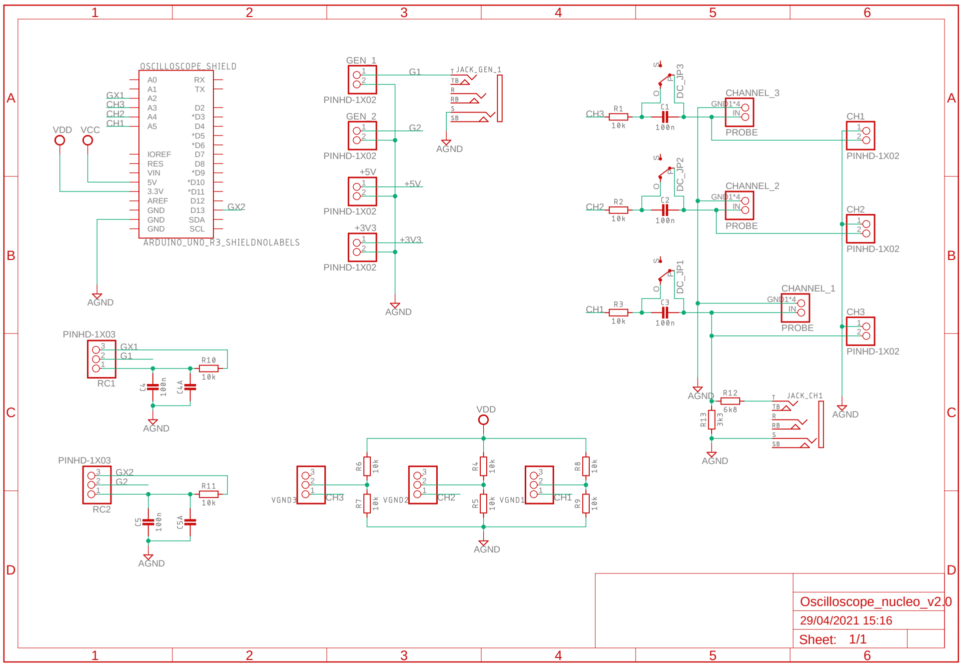


Figure 7.5: Schematic of Leo oscilloscope subboard shield.

Due to covid-19 restrictions, getting to the lab at CTU was not possible very frequently, so I decided to get a LEO oscilloscope running on Nucleo F303RE microcontroller for testing and debugging [32]. To ease the electronic debugging process, I decided to make a shield for Leo oscilloscope that would connect three of the channel inputs of the oscilloscope to BNC connectors for standard oscilloscope probes and to connect one channel input and one generator output to standard 6.3mm mono jacks so that it directly connects the pedal to the generator and channel input to observe pedals feedback.

I designed the shield PCB before the arrival of the Nucleo F303RE, due to delayed shipping, so few circuit features added could help with debugging. Starting with an RC low pass filter on the generator outputs because I was not sure how the output signal would look if it is constructed by high-frequency PWM and it needs to be filtered or not. Another feature is setting the virtual grounds and coupling capacitor on the channel inputs that can be shorted by a switch/pins with jumpers to read DC or AC voltages. Another feature is adding pins for the power supply for general use and pins for individual channels for pinhead cable connections. For channel one, input from 6.3mm jack since the output of the guitar effect pedal is most of the time approximately $+9V$ at maximum, and the signal to Leo channel inputs needs to be less than $+3V3$ there is a voltage divider installed with a 3:1 input to output ratio. The voltage divider adds approximately $2.2k\Omega$ input impedance. However, since we established that guitar pedals usually have around 200Ω

output impedance (more about this topic in circuit design chapter 5.1.8) the channel input is precise enough for electronic debugging.

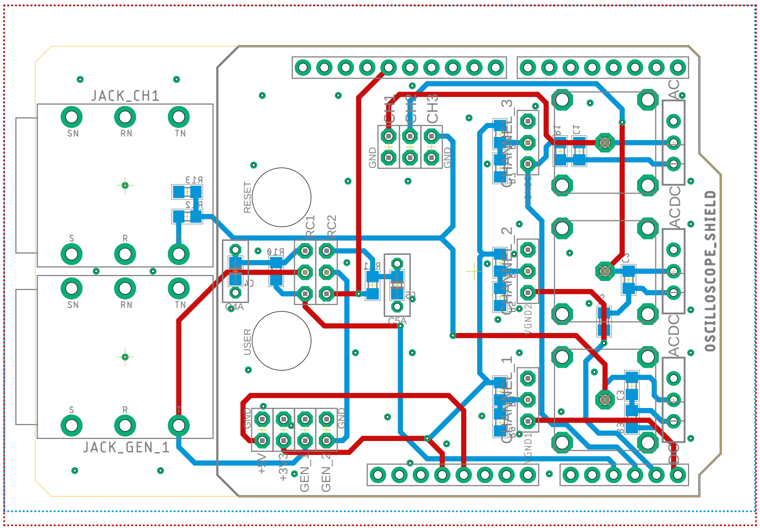


Figure 7.6: PCB of Leo oscilloscope subboard shield.

7.4 Analog effect module example

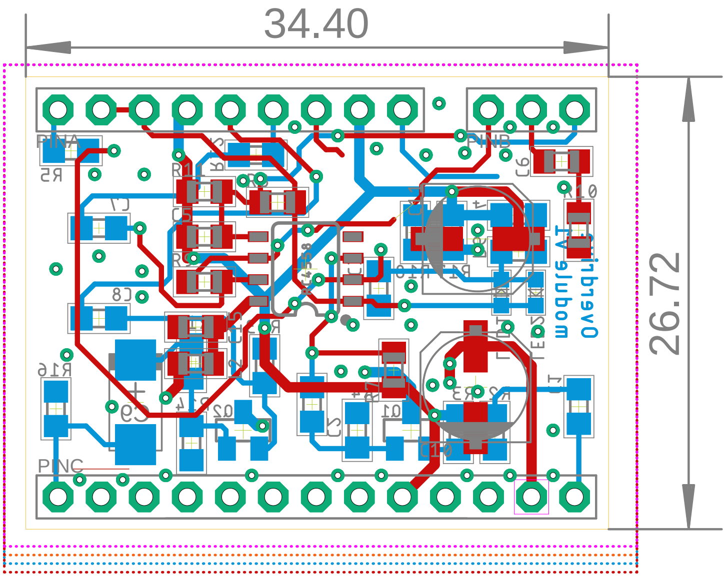


Figure 7.7: PCB of overdrive effect module example.

The digital guitar pedal can be a double guitar pedal (two effects in series), one digital with the FV1 sound processor and the second one with a pedal effect module I designed with the KHDK company. Here there is one example of overdrive effect module PCB shown. They have the whole analog circuit that creates the sound effect placed on the subboard. It plugs via pin rows to the main board (motherboard) with all electromechanical components (poten-

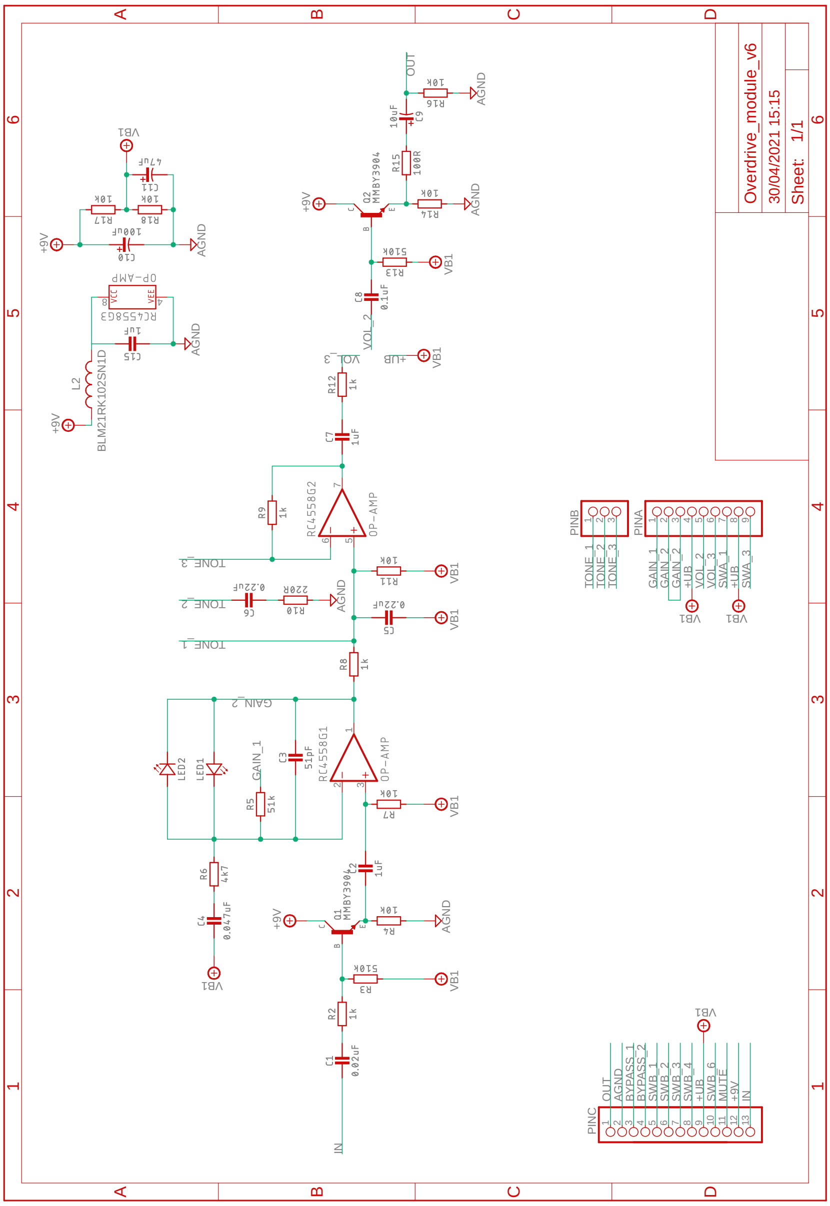


Figure 7.8: Schematic of overdrive effect module example.

tiometers, jack inputs, outputs, and connection to the switching subboard). It has the possibility of six three-pin controls (potentiometers, switches, power section, inputs, and outputs), includes pins for the input and output and power source. The design of the effect module is not a part of this thesis and was designed before, so the circuit or PCB design is not described in detail here.

Part III

The results and conclusion

Chapter 8

Assembling

This chapter shows assembled PCBs of the finished Digital guitar pedal and required additional PCBs for a fully working project.

8.1 Digital guitar pedal with overdrive effect module

There are two fully working digital guitar pedals assembled with eight programs and internal/external switching options. Due to delayed shipping, I did not receive the rotary switch on time, so leavers make the program selection. The PCB was assembled based on the circuit values in circuit design chapter 5. One prototype is assembled with a true bypass subboard for digital effect and module and the other one is assembled with processor-controlled bypass switching for the digital effect and processor-controlled relay bypass for the effect module. PCB design was done correctly with one mistake of the wrong pinout of the $+3V3$ regulator, so it is substituted with the THT option.

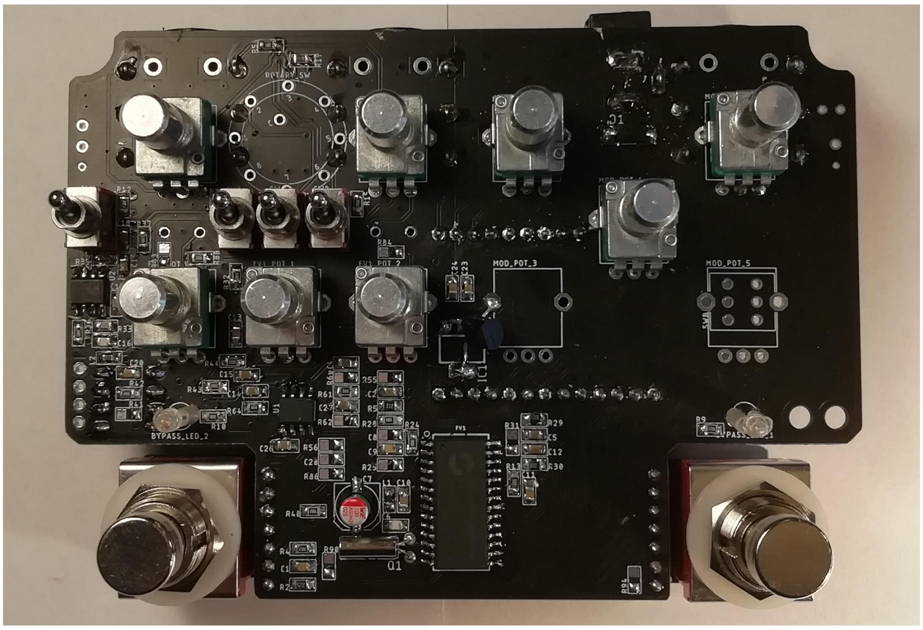


Figure 8.1: Top view of the fully assembled digital guitar pedal with true bypass switching.

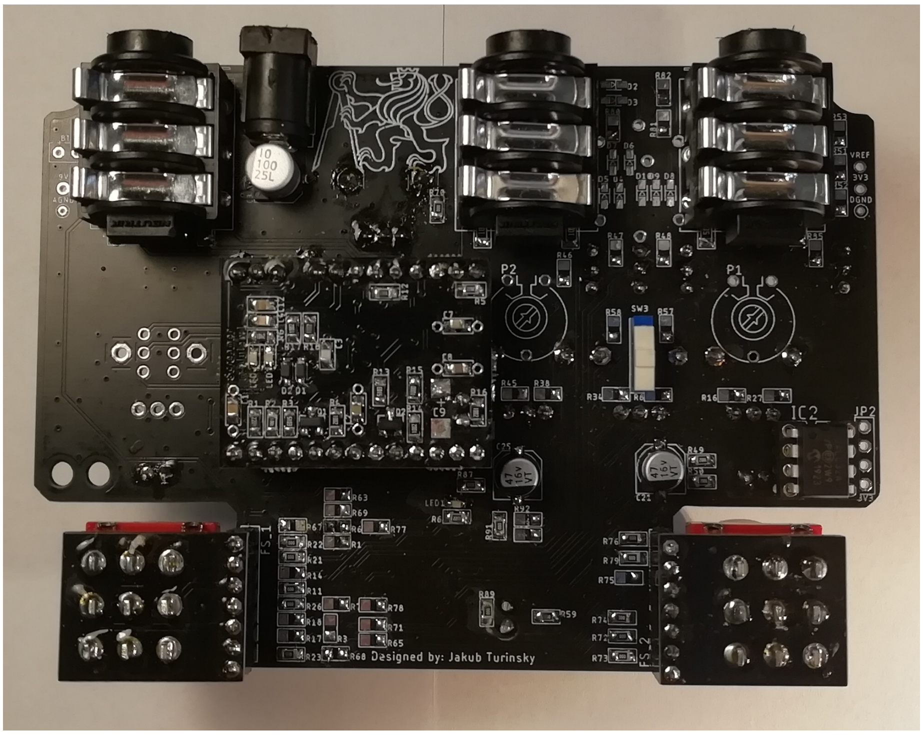


Figure 8.2: Bottom view of the fully assembled digital guitar pedal with true bypass switching.

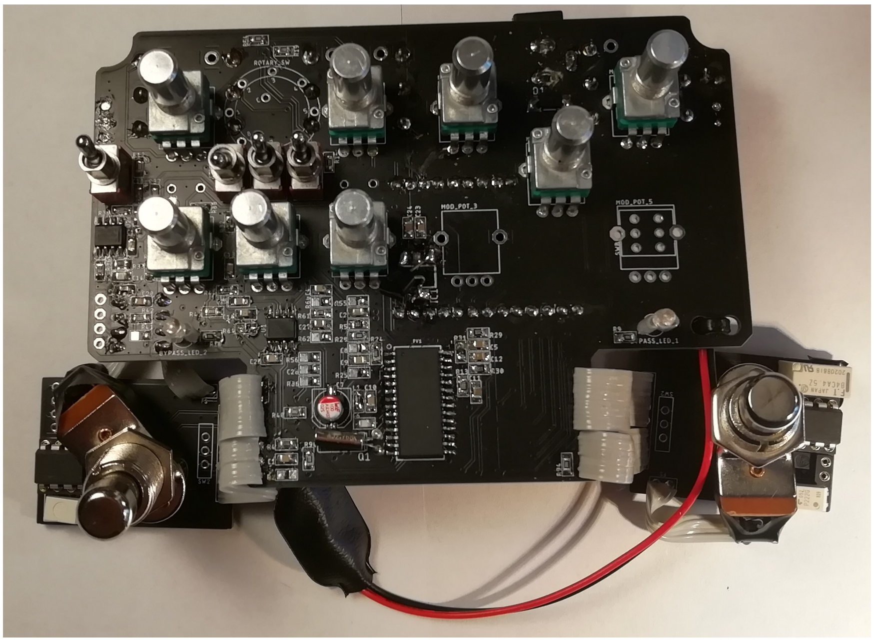


Figure 8.3: Top view of the fully assembled digital guitar pedal with controlled bypass switching.

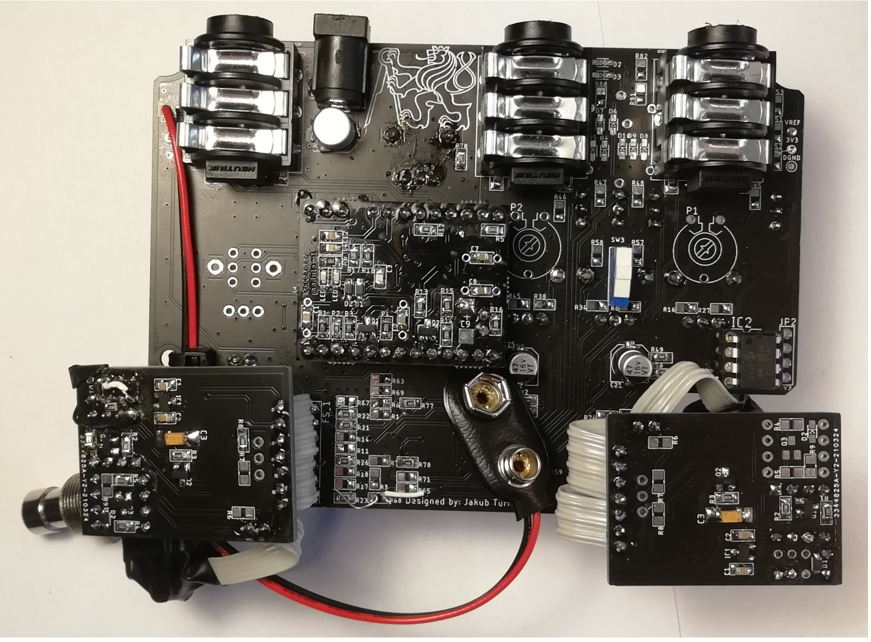


Figure 8.4: Bottom view of the fully assembled digital guitar pedal with controlled bypass switching.

Figure 8.5: Top view of the fully assembled digital guitar pedal in enclosure with true bypass switching connected to signal chain.

Figure 8.6: Angled top view of the fully assembled digital guitar pedal in enclosure with True bypass switching.

8.2 Additinal hardware

To run the finished digital guitar pedal with external (not integrated) programs, you need to program the external EEPROM. For this reason, there is one prototype assembled of the USB external EEPROM programmer 8.8. The programmer had the same problem as the digital guitar pedal with the wrong pinout of the voltage regulator, but there is an option to power it from the digital guitar pedal. I tested programming the memory via a ribbon cable (see on 8.8), and when the cable plugs in, holding only by the force of its weight, it works very reliably (no interruptions occured while loading the programs).

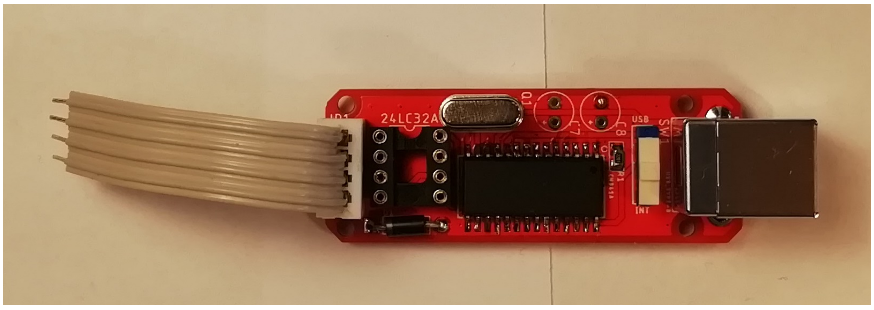


Figure 8.7: External USB EEPROM programmer.

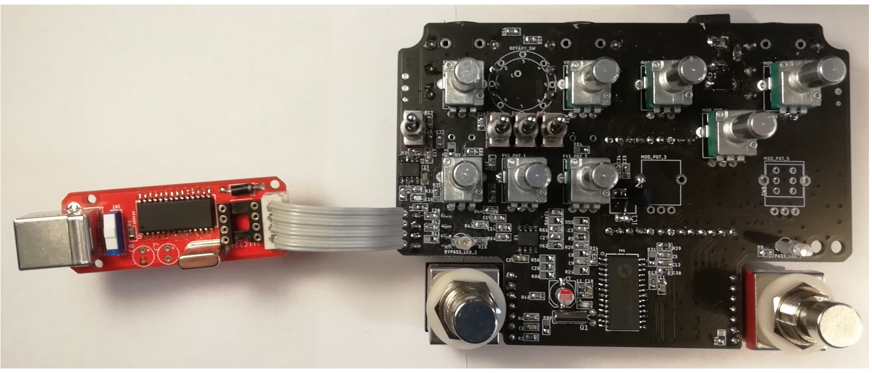


Figure 8.8: Example of use of the external USB EEPROM programmer.

For making the processor-controlled switching option, I designed and assembled PCB that works as a shield for Arduino UNO based on the project, [31].

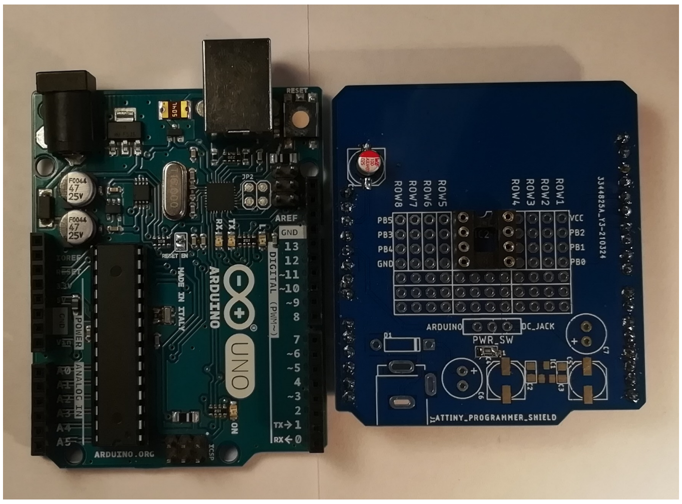


Figure 8.9: Attiny programmer shield for Arduino UNO.

One oscilloscope shield for the Leo oscilloscope was assembled, and it works well. The only problem I observed is that the BNC connectors for the probes are for some probe types too close to each other, so the probe does not fit. But I used narrow probes with metal connectors that fit.

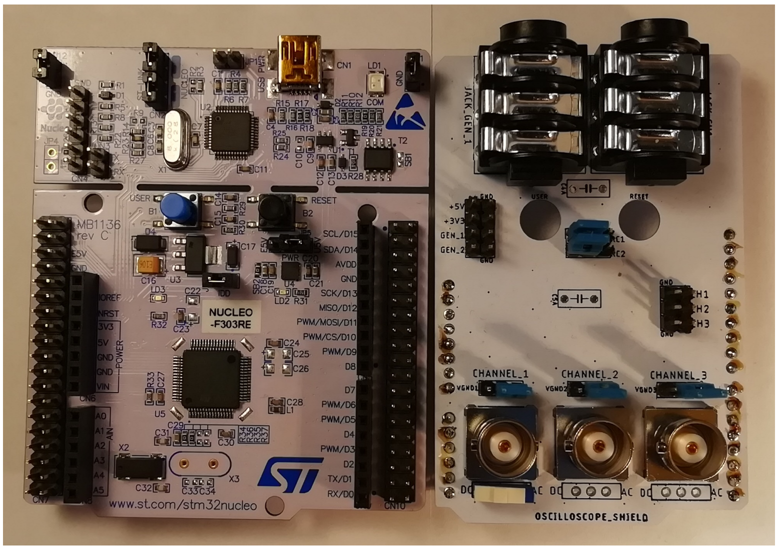


Figure 8.10: Leo oscilloscope shield for Nucleo-F303RE.

Chapter 9

Measurements

9.1 Transfer function of the pedal

All transfer functions were measured with Velleman PCSGU250 oscilloscope in circuit analyzer tool with function generator amplitude set to $V_{PPS} = 1V$ and no offset. The circuit analyzer frequency step was set to 10%. Because the pedal is an audio device, only a hearable spectrum of 20Hz to 20kHz is considered.

9.1.1 Bypass mode

Off mode (or bypass mode)needs to be as flat as possible, so the signal does not change in any frequency range. True bypass (mechanical switch) transfer function was measured to serve as an ideal example for comparing other options. In the first figure 9.1, I compared true bypass to the buffered bypass (see in figure 9.1). It shows a constant amplitude drop across the whole spectrum, but this can is fixable by setting the gain in the mix stage (more about the mix section in 5.1.7). The interesting part is the voltage drop in the frequency bandwidth up to $100Hz$. Bypass switching is required not to have amplitude dependent on frequency because then it functions as a frequency filter. But guitar signal is typically over $150Hz$ (low E string - E_3 first harmonic is about $164Hz$). Even though there is a common practice of detuning the guitar, it would need to detune it by nine half steps (to G_2 first

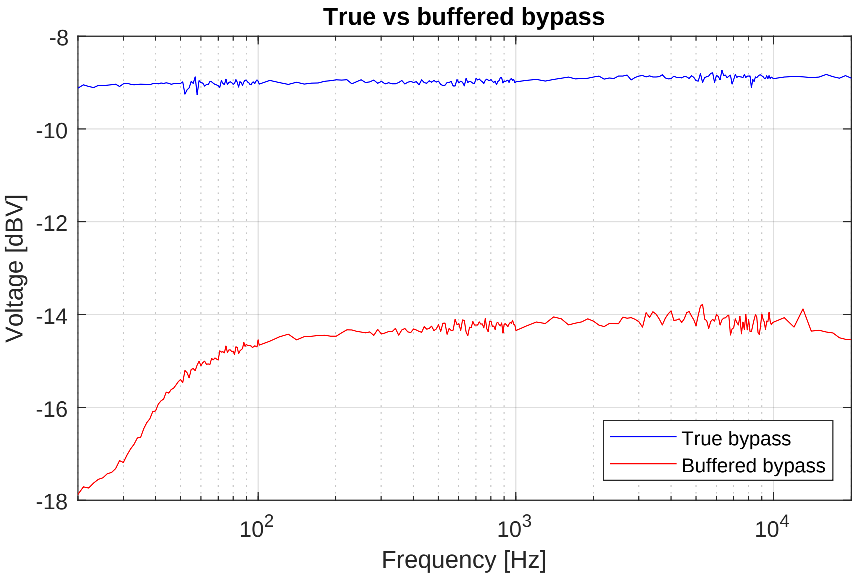


Figure 9.1: Transfer function of true vs buffered bypass.

harmonic that is about $98Hz$) very unlikely to be done. The buffered bypass is then suitable for bypassing the guitar effect but could be unsuitable for instruments with lower output signal frequency, like, for example, bass guitar.

Another measurement I did was comparing true bypass with the relay switching and with the relay switching, including photorelay for muting (more about this topic in 5.2.3). Relay bypass switching with photorelay for muting the pop sound is not a true bypass by definition, even tho the photorelay

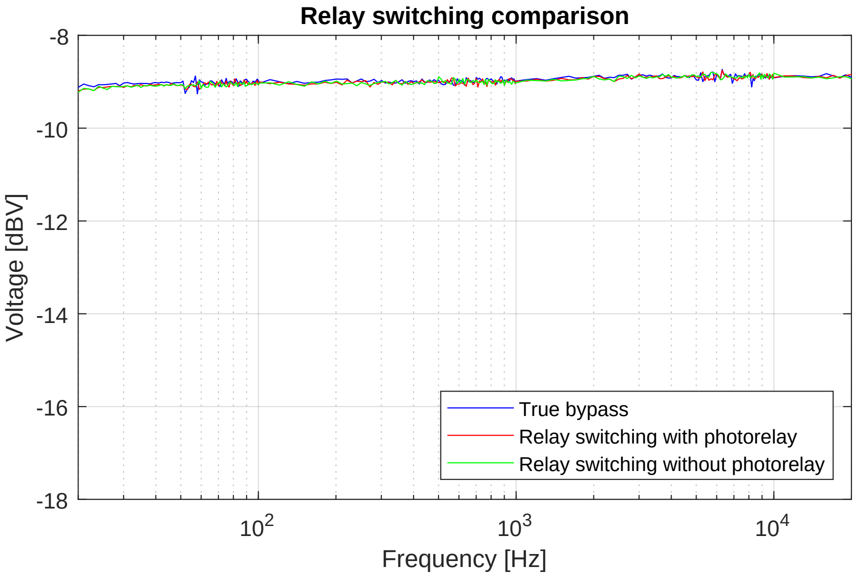


Figure 9.2: Comparison of tre bypass and relay bypass with and without muting photorelay.

has large off-state resistance. Figure 9.2 shows the comparison. The relay bypass and the relay bypass with the photorelay has almost identical transfer function and therefore serve as a good alternative for the true bypass switching.

9.1.2 Effect (on) mode

Because the effects done by the digital guitar pedal are, most of the time, non-linear audio effects, the transfer function is not a great representation. Figure 9.3 shows one non-linear internal reverb effect example for demonstration.

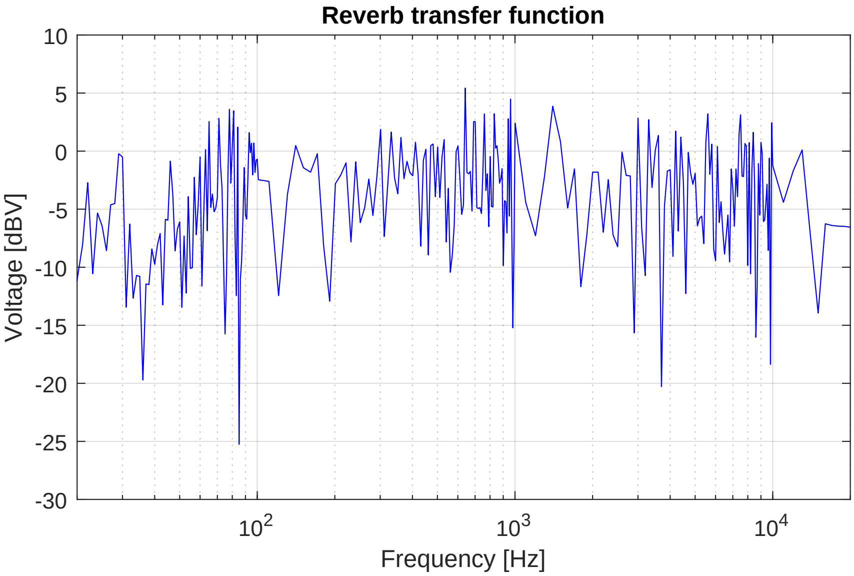


Figure 9.3: Example of non-linear transfer function of reverb effect.

To observe that the FV-1 transfers and reproduces all frequencies in the hearable spectrum, there is a transfer function of an octave effect (sourced from [9]). Potentiometers are set to produce only the dry signal on the output, so it is an effect that creates a digital dry signal on the FV-1 and then mixes with the analog dry signal on the output. This way, it can demonstrate FV-1 delay to the output in the computing process. Figure 9.4 shows the result. There is a noticeable pattern of amplitude drop in the transfer function. It is caused by the delay of the digital dry signal on the output in a specific frequency close to half of the signal's frequency on the input. To prove that, I measured signals on the digital dry (output of the FV-1) and analog dry separately at $f_{input} = 331Hz$ (green dot mark on figure 9.4) the frequency, which is the frequency of the first amplitude drop. It shows on the figure 9.5 that they are phase-shifted from each other by half of the period. It is

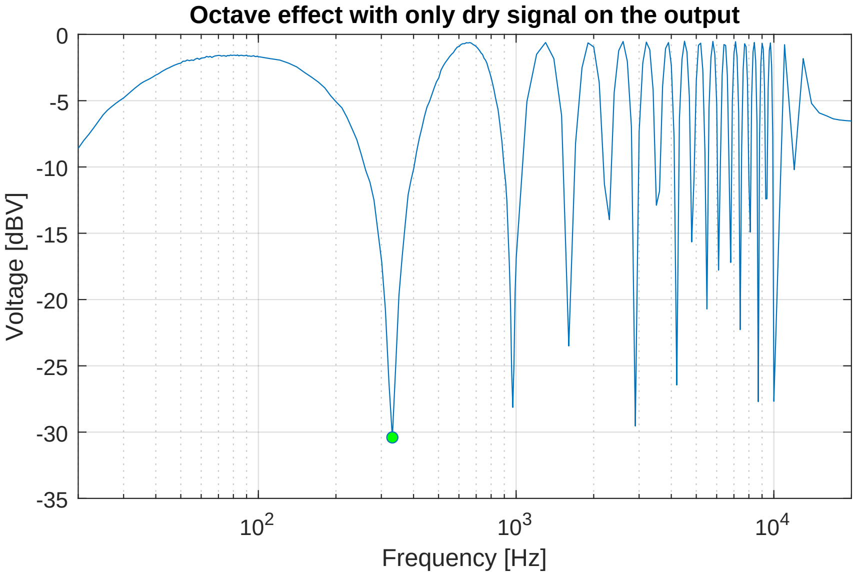


Figure 9.4: Transfer function of an effect that creates digital dry signal on the FV-1 output and than is mixed with the analog dry signal in the mix section.

noticeable that the amplitude of digital dry is higher than dry signal, but this is configured by setting signal amplification in the mix section (more in Circuit design chapter in mix section 5.1.7). With this measurement, we can compute the delay time T_{delay} of the FV-1 processor as half of the input signal period T_{input}:

$$T_{input} = \frac{1}{f_{input}} = \frac{1}{331} \doteq 3.021 ms \Rightarrow T_{delay} = \frac{T_{input}}{2} = 1.510 ms$$

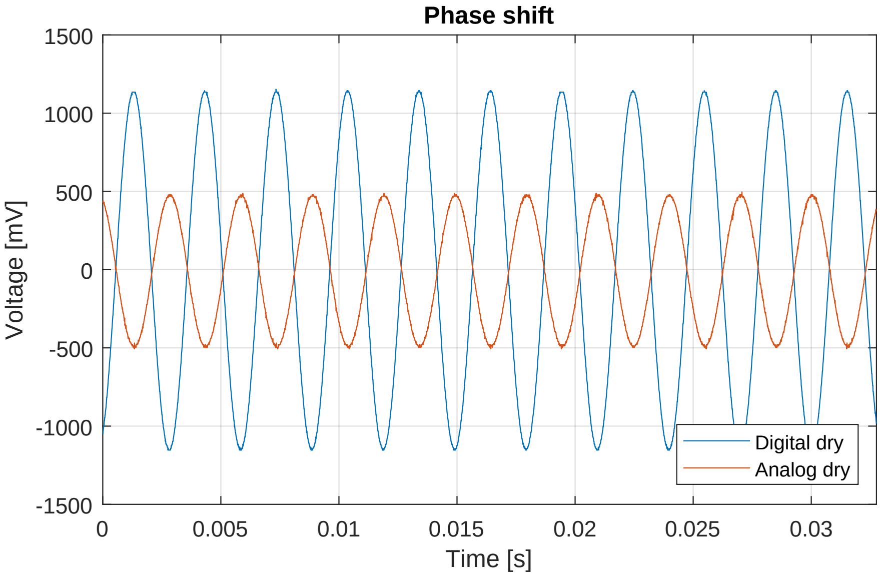


Figure 9.5: Measured digital and analog dry signal at $f_{input} = 331 Hz$.

As an example of the FV-1 output delay, $T_{delay} = 1.510ms$ is short enough to be easily usable.

9.2 Reducing pop noise

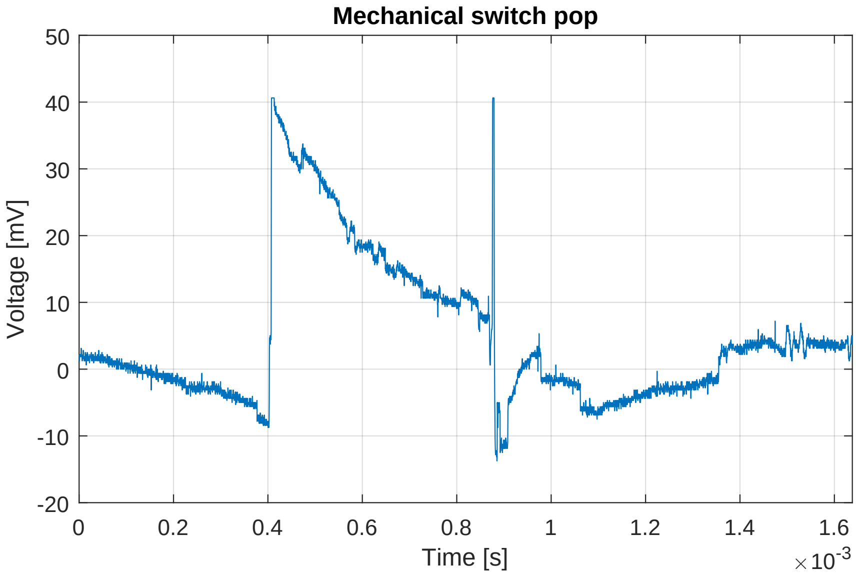


Figure 9.6: Measured digital and analog dry signal at $f_{input} = 331Hz$.

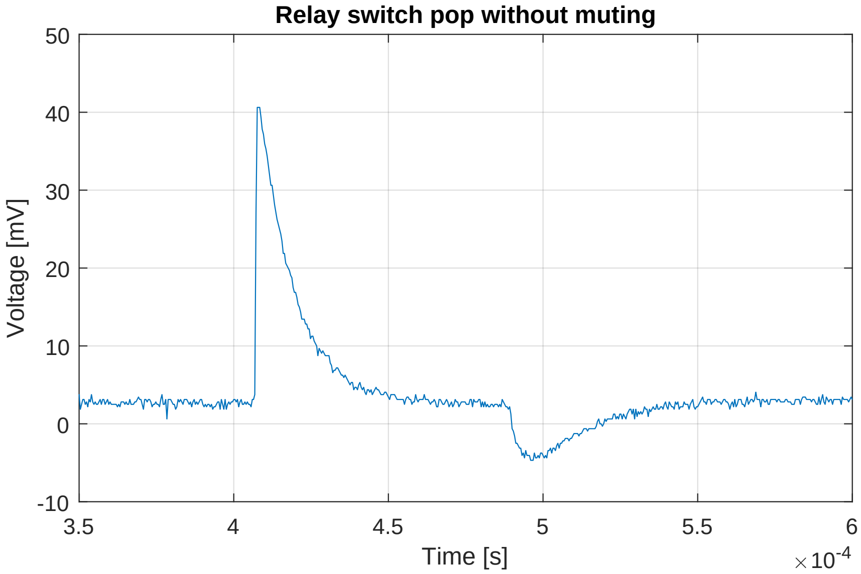


Figure 9.7: Measured digital and analog dry signal at $f_{input} = 331Hz$.

The mechanical switch creates a pop sound when it switches signal path directly. The figure 9.6 shows the measured pulse of a 3PDT mechanical

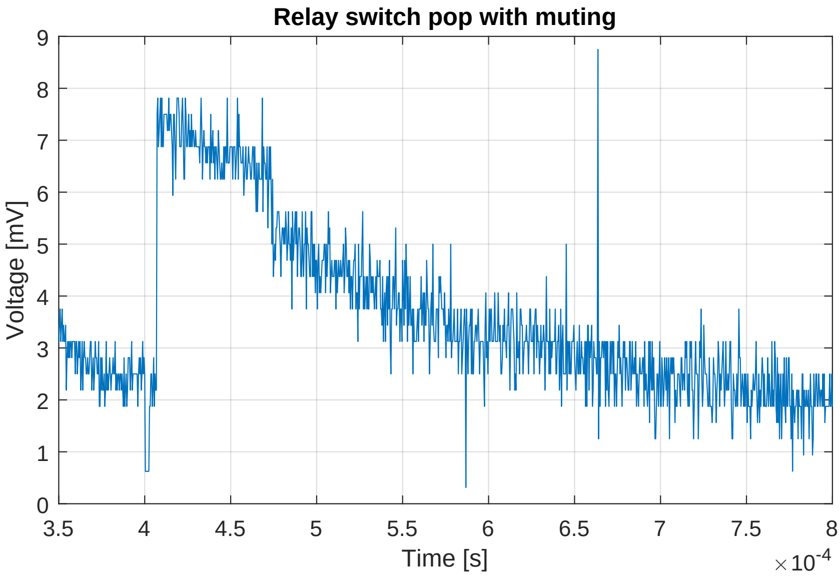


Figure 9.8: Measured digital and analog dry signal at $f_{input} = 331Hz$.

footswitch (see the mechanical switch in 6.4), relay without the muting photorelay (see on figure 9.7) and with the muting photorelay (see on figure 9.8). There is a significant amplitude drop of the muted pop sound by the photorelay, and when plugged into the signal chain directly after the guitar, it is barely audible. The pop sound is inaudible and unmeasurable with an oscilloscope probe, when plugged into the signal chain after some active pedal or after some buffered pedal.

9.3 Power usage

Because the output voltage of the typical power source is fixed to $+9V$ for measuring the power consumption, we measured only DC current with UNI-T UT131A multimeter that has in the range $200mA$ precision of $\pm(1\% + 3)$. Because power usage is measured only to ensure that the pedal does not use more power than standard $300mA$ power sources, two individual states were measured. Pedal with true bypass on the digital effect and effect module and pedal with controlled relay switching on the effect module and controlled buffered bypass on the digital effect. True bypass pedal had both effects on and controlled bypass had buffered bypass on and relay bypass off for first measurements and on for the second. This way, we can estimate how much more current does the controlled bypass switching drain and how much the non-latching relay drain when on.

I did current estimation I_{est} as mean of measured values. Than I calculated

	True bypass	Relay off	Relay bypass on
i [-]	$I_{TB,i}$ $[mA]$	$I_{OFF,i}$ $[mA]$	$I_{ON,i}$ $[mA]$
1	68.1	90.7	120.4
2	68.1	91.1	120.6
3	68.0	90.6	120.4
4	68.1	90.8	120.6
5	68.2	91.0	120.4
6	68.4	90.7	120.5
7	68.3	91.3	120.6
8	68.1	90.6	120.6
9	68.0	91.2	120.5
10	68.1	90.6	120.5

Table 9.1: Pedal power usage measurements.

	True bypass	Relay bypass off	Relay bypass on
	I_{TB} $[mA]$	I_{OFF} $[mA]$	I_{ON} $[mA]$
I_{est}	68.14	90.86	120.51
u_A^2	0.04	0.08	0.02
u_B^2	0.56	0.69	0.86
u_C	0.77	0.88	0.94
u_{ext}	1.55	1.76	1.89
Overall current drain	68.14 ± 1.55	90.86 ± 1.76	120.51 ± 1.89

Table 9.2: Pedal power usage results.

type A uncertainty u_A^2, type B uncertainty u_B^2 and combined type C uncertainty u_C. I assumed normal distribution and calculated extended uncertainty for 95% level of reliability by multiplying it by $k_r = 2 \Rightarrow u_{ext}$. The results are in table 9.2.

Measurements of the power consumption with and without signal on the input were off by insignificant difference for power consumption purposes (approximately $1mA$). We can see that the processor-controlled switching drains approximately $22mA$ more and the relay, when toggled, drains approximately another $30mA$. The current drain of $120mA$ is still in range requirements of $300mA$ current drain (see in requirements chapter 3.1). However, it is outside of the range of a small power source that outputs only $100mA$. For this reason, it would be a significant upgrade to design relay switching for the latching version to fit into the $100mA$ range.

Chapter 10

Conclusion

10.1 Conclusion

The pedal works as a fully functioning digital guitar effect unit. With an effect module, it creates a double effect pedal with many possible combinations (series, parallel, and more, see the block diagram of the main schematic 5.1) that meet standard guitar pedal requirements. The pedal can be powered by a 9V battery or by a standard guitar pedal power source with at least $150mA$ output current without the need to disconnect the battery if plugging in the power adapter. Pedal inputs and outputs are standard 6.3mm jacks, so there is no need for cable reduction, and the whole pedal can fit within the Hammond 1590BB enclosure with the chosen layout. It can be turned on or bypassed by foot press force with several bypass switching options: True bypass with 3PDT footswitch, buffered bypass with 3PDT footswitch, processor-controlled relay bypass switching as an alternative to true bypass switching with muting pop noise option, and processor-controlled buffered bypass. Digital guitar effect includes an output for expression pedal for controlling the amplitude of the signal that goes to the FV-1 sound processor. External circuits and PCBs were designed and tested for the digital guitar effect, including a custom USB programmer for the EEPROM, a shield for an Attiny processor programmer for Arduino UNO, and a shield for the LEO oscilloscope for faster and easier testing. That creates a very versatile guitar pedal effect developing the platform with many possible outcomes.

10.2 Future improvements

The $+3V3$ SMD regulator PCB package has the wrong pinout, so it had to be replaced by the THT version and soldered by hand for this first version. The pinout needs to be fixed for it to be soldered properly. There was not an SMD crystal oscillator for the FV-1 available when designed, so there is a THT version in this prototype that needs to be replaced by SMD to meet the requirements. Relay switching takes place on a separate subboard connected with a ribbon cable to the main board. That has two problems. First, it does not have mechanical support to the enclosure, so there is a possibility of shortages. The second is that one of the main advantages of relay switching is that it can be physically moved on the PCB away from the bypass switch. This can prevent noise accumulating on the input signal when drafted across the whole board (from the input jack on the top to the bottom where is the bypass switch) by placing components of the input buffer close to the relay bypass switch and close to the input jack.

To improve pedals possibilities as a developing platform, it lacks the possibility of disconnecting analog dry signal path to the output because some digital guitar effects cannot have dry signal mixed in on the output. In this prototype, it can be done by desoldering components on the dry signal path. However, it would make developing digital audio effects faster and easier if there would be a mechanical switch. I designed the main board with THT EEPROM memory with pins for reprogramming the EEPROM mainly to test the reliability of the pin connections. I tested this solution, and it is reliable, so it should be replaced by the SMD version for a future prototype. Another change in the next prototype is making the pins reprogramming the memory asymmetric to make sure they do not connect in reverse when programmed in production, causing damage.

Appendices

Appendix A

List of attachments

The attachments consist of all schematics and board pdfs, CSV with the typical application partlist, and program for the controlled bypass Attiny85 processor:

- `Attachments`
  - `Main board`
    - `FV1_dev_v1_drawing.pdf`
    - `FV1_dev_v1.4_schematic_finished.pdf`
    - `FV1_dev_v1.4_PCB_top.pdf`
    - `FV1_dev_v1.4_PCB_bottom.pdf`
    - `FV1_dev_v1.4_PCB.pdf`
    - `FV1_dev_v1.4.csv`
  - `Bypass subboards`
    - `FS_v1_schematic.pdf`
    - `FS_v1_board.pdf`
    - `FS_OK_schematic.pdf`
    - `FS_OK_board.pdf`
    - `Attiny_FS_schematic.pdf`
    - `Attiny_FS_board.pdf`
    - `Non-Latching_program.ino`
  - `Additional HW`
    - `Attiny_programmer_schematic.pdf`
    - `Attiny_programmer_board.pdf`
    - `Oscilloscope_nucleo_schematic.pdf`
    - `Oscilloscope_nucleo_board.pdf`
    - `USB_programmer_schematic.pdf`
    - `USB_programmer_board.pdf`

Appendix B

Partlist of a typical assembling

Below you can find table B.1 of component values for a typical main board assembly with true bypass. The partlist excludes values of the potentiometers of the effect module and jumper values for plugging the effect module into the main circuit of the mainboard (for more details see 5.9).

Qty	Value	Device	Package	Parts
2		PAD_TEST_POINT	PAD_TEST_POINT	AGND, DGND
3		PAD_WIRING_35MIL	PAD_WIRING_35MIL	3V3, 9V, VREF
1	JACK_DC_PC-MOUNT _2.1MM_ALT	JACK_DC_PC-MOUNT _2.1MM_ALT NO_THERMALS	JACK_DC_PC-MOUNT_2.1MM _NO_THERMALS	DC_JACK_9V
3	JACK_NEUTRIK_NMJ6HCD2	JACK_NEUTRIK_NMJ6HCD2	JACK_NEUTRIK_NMJ6HCD2	EXPRESSION, INPUT, OUTPUT
3	JACK_SHIELD_FCR14422	JACK_SHIELD_FCR14422	JACK_SHIELD_FCR14422	EXP_SHIELD, INPUT_SHIELD, OUTPUT_SHIELD
4	SWITCH_SP_PC-MOUNT _SUB-MINI	SWITCH_SP_PC-MOUNT _SUB-MINI	SWITCH_SP_PC-MOUNT_SUB-MINI	SW0, SW1, SW2, SW4
1	450301014042	SWITCH_SP_PC-MOUNT _SUB-MINISWITCH_ON_PCB	EG1218	SW3
24	0R	RESISTOR_0805	R0805	R11, R21, R22, R23, R24, R26, R28, R42, R54, R59, R61, R63, R65, R67, R70, R72, R73, R74, R76, R79, R87, R88, R89, R91
1	100R	RESISTOR_0805	R0805	R13
4	100k	RESISTOR_0805	R0805	R4, R32, R36, R37
1	100n	CAP_0805_MLCC	C0805_MLCC	C1

Qty	Value	Device	Package	Parts
1	100uF	CAP_ELECTROLYTIC_D	CAP_ELECTROLYTIC_D	C3
6	10k	RESISTOR_0805	R0805	R9, R10, R35, R40, R49, R50
1	10u	CAP_ELECTROLYTIC_D	CAP_ELECTROLYTIC_D	C7
1	120p	CAP_0805_MLCC	C0805_MLCC	C16
1	15p	CAP_0805_MLCC	C0805_MLCC	C6
6	1M	SPACER_1206_RES	C1206_MLCC	SP1, SP2, SP3, SP4, SP5, SP6
1	1N4007	DIODE-MELF-MLL41	MELF-MLL41	D1
3	1k	RESISTOR_0805	R0805	R5, R29, R30
1	1n	CAP_0805_MLCC	C0805_MLCC	C9
11	1u	CAP_0805_MLCC	C0805_MLCC	C5, C10, C11, C12, C15, C17, C18, C19, C20, C23, C24
1	20k	RESISTOR_0805	R0805	R12
2	220R	RESISTOR_0805	R0805	R6, R39
6	22k	RESISTOR_0805	R0805	R15, R19, R20, R33, R43, R44
1	24LC32AP	24LC32AP	DIL8	IC2
1	2M2	RESISTOR_0805	R0805	R2
1	2n2	CAP_0805_MLCC	C0805_MLCC	C13
5	2u2	CAP_0805_MLCC	C0805_MLCC	C2, C4, C14, C26, C27
1	32.768 kHz	CRYSTALTC38H	TC38H	Q1

Qty	Value	Device	Package	Parts
3	47u	CAP_ELECTROLYTIC_D	CAP_ELECTROLYTIC_D	C21, C22, C25
1	9V_BATTERY-SNAP	9V_BATTERY-SNAP	PADS_BATTERY_SNAP_WIRING	BT1
4	B100K	POTENTIOMETER_9MM_PC_MOUNT_V	POTENTIOMETER_9MM_PC_MOUNT_V	FV1_POT_0, FV1_POT_1, FV1_POT_2, VOLUME
1	B25K	POTENTIOMETER_9MM_PC_MOUNT_V	POTENTIOMETER_9MM_PC_MOUNT_V	EFFECT
2	BLM21RK102SN1D	BLM21RK102SN1D	L0805	L1, L2
1	FV1	FV1	SOIC-28	FV1
1	MCP1703T-3302E/DB	AP2210N-3.3TRG1SOT-223	SOT-223	IC1
1	MINI_ROTARY	MINI_ROTARY	MINI_ROTARY	ROTARY_SW
2	NP	CAP_0805_MLCC	C0805_MLCC	C8, C28
1	NP	CAP_TANTAL_SMD	CAP_TANTAL_SMD_C	C29
9	NP	DIODE_SOD-323	SOD-323	D2, D3, D4, D5, D6, D7, D8, D9, D10
5	NP	POTENTIOMETER_9MM_PC_MOUNT_V	POTENTIOMETER_9MM_PC_MOUNT_V	MOD_POT_1, MOD_POT_2, MOD_POT_3, MOD_POT_4, MOD_POT_5

Qty	Value	Device	Package	Parts
46	NP	RESISTOR_0805	R0805	R1, R3, R7, R8, R14, R16, R17, R18, R25, R27, R31, R34, R38, R41, R45, R46, R47, R48, R51, R52, R53, R55, R56, R57, R58, R60, R62, R64, R66, R68, R69, R71, R75, R77, R78, R80, R81, R82, R83, R84, R85, R86, R90, R92, R93, R94
1	NP	SWITCH_DP_PC-MOUNT_SUB-MINI-DP3T-TM_PC_VMX	SWITCH_DPDT_PC-MOUNT_SUB-MINI_VIMEX	SWB_1
2	NP	TRIM_SIMON	PT-10	P1, P2
1	PINHD-1X03	PINHD-1X03	1X03	PINB_1
1	PINHD-1X04	PINHD-1X04	1X04	JP2
2	PINHD-1X07	PINHD-1X07	1X07	FS_1, FS_2
1	PINHD-1X09	PINHD-1X9	1X09-BIG	PINA_1
1	PINHD-1X13	PINHD-1X13	1X13	PINC_1
2	RC4558	OPAMP_DUAL-RC4558-SMT_SOIC-8	SOIC-8	U1, U2
1	RED	LED_0603	LED_0603	LED1

Qty	Value	Device	Package	Parts
2	RED	LED_3MM_T1	LED_3MM_T1	BYPASS_LED_1, BYPASS_LED_2

Table B.1: Partlist of a typical assembling with true bypass version with reprogramming enabled and program selection with leavers.

Appendix C

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