

## Bachelor Thesis

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### Concept and Development of an Audio Device and Microcontroller Interface Board for Communication with Sensors and Drives in an Electronic Guide Dog

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Concept and Development of an Audio Device and  
Microcontroller Interface Board for Communication with  
Sensors and Drives in an Electronic Guide Dog

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**Thema der Arbeit**

Konzeptionieren und Entwickeln einer Platine für Tongerät und Mikrokontrollerschnittstellen zur Kommunikation mit Sensoren und Treibern eines Elektronischen Blindenführhundes

**Stichworte**

Signalwandlung, Audioverstärker, Platinenlayout, Blindenführhund, Tiva (Mikrokontroller), Schaltplan zeichnen, Schaltungsentwicklung

**Kurzzusammenfassung**

In dieser Thesis wird ein Konzept für eine Schnittstellenplatine erstellt. Die Schnittstellenplatine dient zum Bereitstellen verschiedener Kommunikationssysteme zur Kommunikation des Mikrokontrollers mit verschiedenen Sensoren und Treibern. Dazu werden Signalwandler auf der Platine benötigt. Um mit der geführten Person kommunizieren zu können, wird eine Audioeinheit bestehend aus einem Audio Codec und Audio Verstärkern auf die Platine aufgebaut. Desweiteren werden in dieser Thesis die dafür benötigten Bauteile festgelegt, die Schaltungen entwickelt und die Platine entworfen.

**Max Fischer**

**Title of Thesis**

Concept and Development of an Audio Device and Microcontroller Interface Board for Communication with Sensors and Drives in an Electronic Guide Dog (EGD)

**Keywords**

Signal conversion, audio amplifier, circuit board layout, electronic guide dog (EGD), Tiva (microcontroller), drawing circuit diagram, circuit development

**Abstract**

In this thesis a concept for an interface board is developed. The interface board is used to provide different communication systems for the communication of the microcontroller with different sensors and drivers. For this purpose, signal converters are required on the board. To be able to communicate with the guided person, an audio unit consisting of an audio codec and audio amplifiers is built on the board. Furthermore, in this thesis the required components are determined, the circuits are developed and the board is designed.

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# 1. Introduction

Close relationships between dogs and visually handicapped humans are proven by wall paintings until back in to ancient times[3]. The disadvantages of an guide dog are the complex and expensive education, to take care of the dogs consumes much time and money again and some people are afraid of dogs. In the digital era the dog also needs some functional updates for example, the electronic guide dog (EGD) should be able to navigate you to your destination or tell you which bus is standing in front of you.

These functions are only possible for an electronic guide dog. To navigate the guided person save to its destination the electronic guide dog needs many different sensors, actuators and signal processors. All these parts have to communicate with the main controller. While the developing process of the electronic guide dog is going on it is necessary that some parts need to be changed. To support all of these changes that can occur on the development process the MSA Board is required. The MSA Board supports all sorts of connection for the peripheral systems with the main controller.

## 1.1. Chapter Overview

After the introduction for this bachelor thesis, this chapter provides an orientation for the following chapters about the development of an MSA Board for the development of an electronic guide dog.

Chapter 1 is about the motivation to develop this MSA Board, provides an short overview about the following chapters. It also contains an overview about a possible elctrical structure of the whole electronic guide dog project and where this thesis is located inside the electronic guide dog project. The state of the environmental Hardware surrounding the MSA Board is also shown in chapter 1.

Chapter 2 provides a set of basics and theory required to develop the concept into a possible solution for the MSA Board of the electronic guide dog. It contains example circuits and equation necessary to develop the concept (chapter 4) into the MSA Board.

Chapter 3 is a list of requirements placed on the MSA Board. It is divided in circuit requirements and board requirements. The circuit requirements are seperated after requirements concerning the power supply, the audio signals, the audio amplifier, other signal converters and the connectors to other systems of the electronic guide dog.

Chapter 4 describes a concept to solve the listed requirements and is divided in different parts containing the schematic circuits needed on the MSA Board and a layout concept for the later circuit board.

Chapter 5 lists the Hard- and Software tools used to concept and develop the MSA Board and to illustrate the documentation.

Chapter 6 describes the developed circuits on the MSA Board and the resulting circuit board layout.

Chapter 7 is about the tests done on the circuits before finalizing the circuit diagrams and ordering the Boards. This tests are testing the functionality, the power consumption, performance and for some parts the frequency stability.

Chapter 8 describes the assembling process of the MSA Board.

Chapter 9 contains a review of the previous chapters and summarize it into a final statement.

The Bibliography (Page 46) is a list of resources used to create this Thesis.

Appendixes A, B, C, D, E, F, G, H, I and J are containing material that doesn't fit into the thesis but is important. For example, MATLAB scripts, circuit diagrams, board layouts, a material list, pin lists and pictures of the assembled MSA Boards.

A Declaration (Page 78) that this thesis is done by my self closes the thesis.

## 1.2. Project Overview

This chapter provides an overview about the situation at the electronic guide dog at the start of the thesis and gives an orientation where the thesis is located inside the electronic guide dog.

### 1.2.1. Electrical Architecture

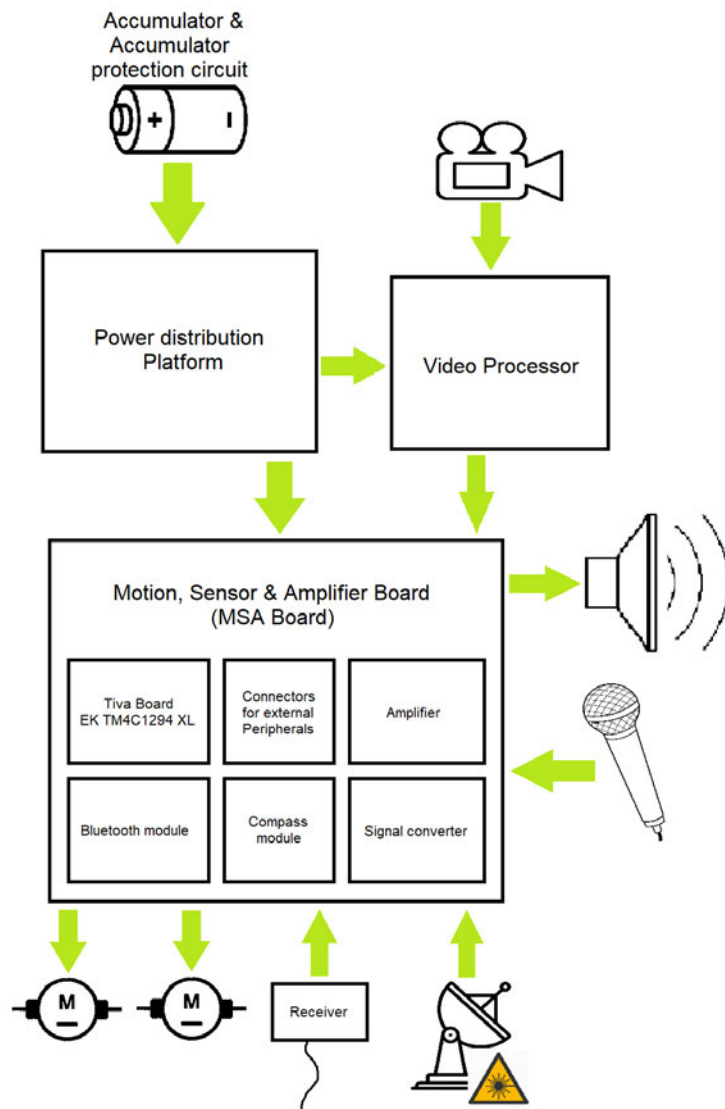


Figure 1.1.: System Overview[4, 5, 6, 7, 8, 9, 10]

As shown in figure 1.1 the MSA Board is not the only system in the electronic guide dog and at the moment the MSA Board has to operate two engine drivers, an RC receiver, a laser radar, a microphone and a speaker. A time of flight camera sends its data to a video processor which is communicating with the main controller. All these systems are powered by an accumulator that is connected to a power distribution platform. The power distribution platform generates different supply voltages out of the accumulator voltage.

Directly mounted on the MSA Board are connectors to connect the previously mentioned systems with the MSA Board, the main controller (Tiva Board EK TM4C1294XL)[11], a audio amplifier, a bluetooth module, a compass module and signal converters.

### 1.2.2. Chassis

The chassis of the electronic guide dog is a Bosch BCH6L2560/04 vacuum cleaner [12]. The disassembled vacuum cleaner is shown in the following Figure 1.2.



Figure 1.2.: Chassis Overview disassembled vacuum cleaner

Shown in Figure 1.2 is the disassembled vacuum cleaner with only the accumulator unit and its electronic left inside used as power source for the electronic guide dog. As shown in Figure 1.2 the accumulator unit consists of a series connection of 7 Lithium cells. The cell management and voltage monitoring for each cell is executed by the shown electronic. The disassembly of the filter unit leaves space to assemble the electronic guide dog parts inside the vacuum cleaner.

## 2. Fundamentals

This chapter provides some basics used for the development of the MSA Board in the following chapters.

### 2.1. Human Ears

A young humans ear can hear sounds with a frequency of 16  $Hz$  up to a frequency of 20  $kHz$ . The human voice can reach frequencies from 100  $Hz$  to 6  $kHz$  [13].

### 2.2. RC Low pass

The RC low pass is a first grade low pass that consists of a resistor and a capacity. Its purpose is to filter frequencies above the cut-off frequency  $f_g$  out of a signal with a frequency lower then the cut-off frequency[14]. Figure 2.1 shows the Circuit diagram of a RC low pass.

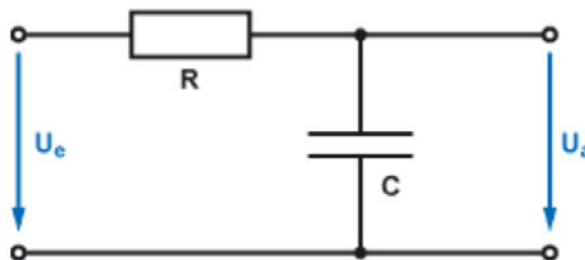


Figure 2.1.: Circuit diagram of an RC Low pass [14]

As seen in figure 2.1 the RC low pass consists in a series of a resistor and a capacitor. The cut off frequency  $f_g$  of the RC low pass is given by the following equation 2.1.

$$f_g = \frac{1}{2 \cdot \pi \cdot C \cdot R} \quad (2.1)$$

To calculate a resistor R with a given cut-off frequency the equation 2.1 will be converted to equation 2.2 [14].

$$R = \frac{1}{2 \cdot \pi \cdot C \cdot f_g} \quad (2.2)$$

### 2.3. Transmission capacities

A transmission capacity is used to connect an alternating signal to systems with different direct voltages. The transmission capacitor cuts off direct voltages. Alternating signals can pass right through it. In serials with a resistor (internal resistor of the connected systems, load resistors) the transmission capacitor forms an RC high pass [15]. Figure 2.2 shows the circuit diagram of a RC high pass.

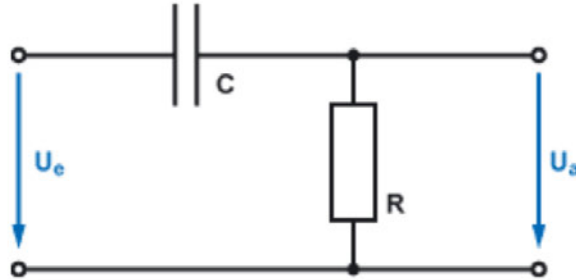


Figure 2.2.: Circuit diagram of an RC High pass [16]

A high pass is designed to do the opposite of a low pass. Like that it cuts off all frequencies below the cut-off frequency and let all frequencies above it pass. To calculate the cut-off frequency and R equation 2.1 and equation 2.2 are used again [16].

### 2.4. Voltage divider

A voltage divider (shown in figure 2.3) consists of two Resistors in a serial connection. It is used to divide a voltage into partial voltages [17].

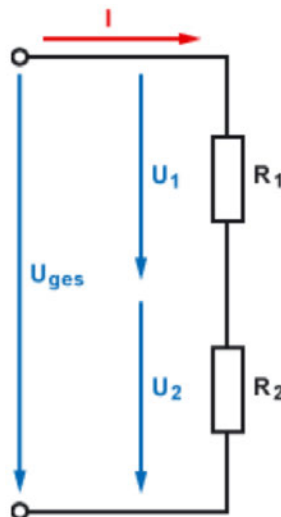


Figure 2.3.: Circuit diagram of an Voltage divider [17]

In this thesis the outputs of the voltage dividers are connected to inputs with a high resistance. Because of that the following equation 2.3 is used for the unloaded voltage divider.

$$U_2 = \frac{U_{ges} \cdot R_2}{R_1 + R_2} [17] \quad (2.3)$$

Following that  $R_1$  is calculated by the following Equation 2.4.

$$R_1 = \frac{U_{ges} \cdot R_2}{U_2} - R_2 \quad (2.4)$$

## 2.5. Non inverting Amplifier with OP Amplifier

The non inverting amplifier consists of a operation amplifier and voltage divider[18].

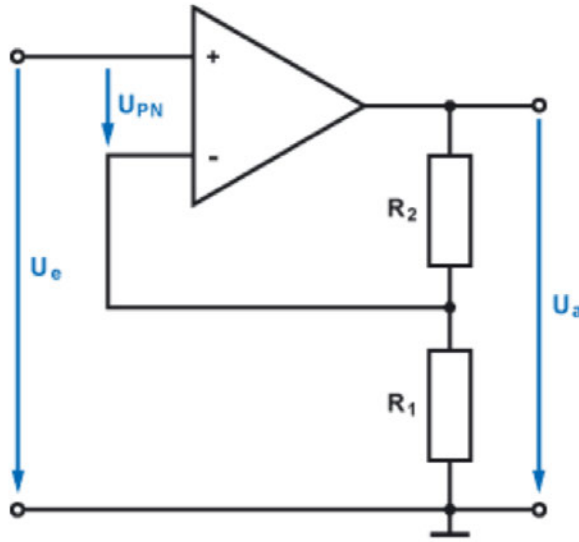


Figure 2.4.: Circuit diagram of a Non-Inverting Amplifier with an Operational Amplifier [18]

As shown in figure 2.4 the operation amplifier has a non inverting and an inverting input. If a voltage divider is connected to the amplifier output and to the inverting input of the amplifier as shown in figure 2.4, it acts as a feedback. With the feedback the amplifier tries to get the same voltage on both inputs ( $U_{PN} = 0V$ ). The amplification factor of the amplifier now depends on the ratio of  $R_1$  and  $R_2$  (equation 2.6) [18].

$$V_u = \frac{U_a}{U_e} \geq 1 \quad (2.5)$$

$$V_u = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1} \quad (2.6)$$

Following that the Resistor  $R_1$  is calculated by changing Equation 2.6 into the following Equation

$$R_2 = V_u \cdot R_1 - R_1 = (V_u - 1) \cdot R_1 \quad (2.7)$$



## 2.6. Inverting Amplifier with OP Amplifier

The inverting amplifier tries to equal both inputs too ( $U_{NP} = 0V$ ). The difference is, the input signal is connected to the inverting input (figure 2.5)[19].

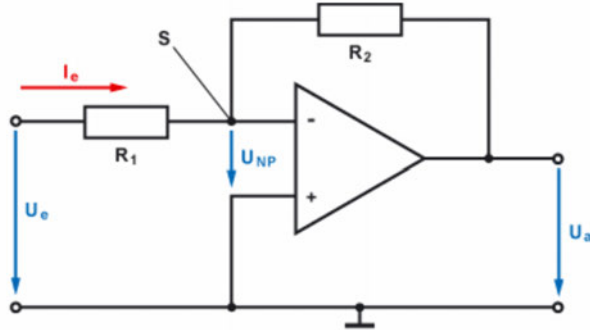


Figure 2.5.: Circuit diagram of an inverting Operational Amplifier [19]

The difference in the circuit diagram causes a change in the equation to calculate the amplification factor. An advantage of the different equation 2.9 is the possibility to create an amplification factor smaller than one [19]. With an amplification factor smaller than one it is possible to build filters directly into the amplifier circuits.

$$V_u = \frac{U_a}{U_e} \quad (2.8)$$

$$V_u = -\frac{R_2}{R_1} \quad (2.9)$$

## 2.7. Complementary Serial Push-Pull Amplifier

The complementary serial push-pull amplifier shown in figure 2.6 is used as a current amplifier in this thesis. It consists of the resistors  $R_1$  and  $R_2$ , the diodes  $D_1$  and  $D_2$ , the NPN transistor  $T_1$  and the PNP Transistor  $T_2$ . The capacitor  $C_K$  is a transmission capacitor (chapter 2.3) at the output of the amplifier. Bipolar transistor are current amplifiers. They amplify the current flowing between base and emitter to the collector. The current in a NPN Transistors flows from the Base and from the collector to the emitter. In PNP transistor it is the other way round. With that a NPN transistor is used to amplify the half wave of a signal and a PNP is used to amplify the negative half wave of a signal. The base emitter resistance depends on the base emitter voltage  $U_{BE}$  and is not linear. A consequence of this is a voltage offset on  $U_{BE}$  needed to unlock the transistors. To pre-load the transistors with this voltage offset is the purpose of the diodes and resistors[20, 21, 22].

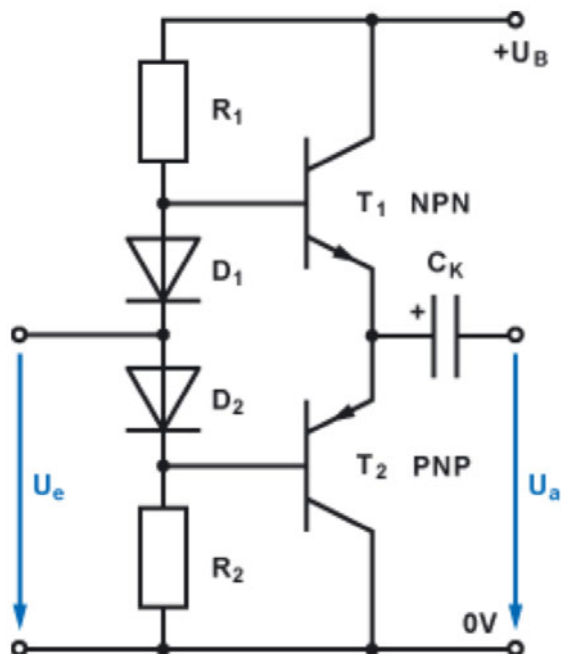


Figure 2.6.: Circuit diagram of a Complementary Serial Push-Pull Amplifier [21]

## 2.8. TLV431

The TLV431 is a low voltage precision shunt regulator. It creates a output voltage based on an internal reference voltage  $V_{ref}$  of  $1.24\text{ V}$ . As a shunt regulator it has an internal transistor to convert excessive powers into heat. Based on that the TLV431 is used to create reference voltages in this thesis.

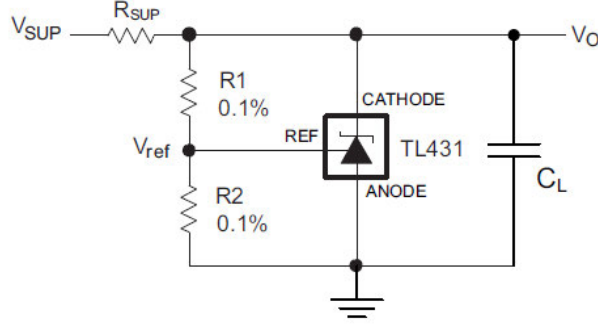


Figure 2.7.: Circuit diagram of a shunt regulator using a TLV431 [23]

As shown in figure 2.7 the TLV431 does not stand alone.  $R_{SUP}$  limits the current in the TLV431 circuit.  $R_1$  and  $R_2$  form a voltage divider required to define an output voltage of the TLV431 other than  $1.24\text{ V}$ . The following equation 2.10 [23] is used to calculate the output voltage  $V_O$  of the TLV431.

$$V_O = \left(1 + \frac{R_1}{R_2}\right) \cdot V_{ref} \quad [23] \quad (2.10)$$

Following that, Equation 2.10 is changed to calculate  $R_1$ .

$$R_1 = \left(\frac{V_O}{V_{ref}}\right) \cdot R_2 - R_2 = \left(\frac{V_O}{V_{ref}} - 1\right) \cdot R_2 \quad (2.11)$$

## 2.9. Heat Sink calculation

As mentioned before (chapter 4.2.3 and chapter 2.7) the audio amplifier uses transistors to amplify the output current for the speaker. These power transistors have to be cooled or else the power output of the transistors decreases [20]. To calculate the maximum heat resistance the heat sink used to cool the transistors can have, the following equation 2.12 is used.

$$\begin{aligned}
 P_v &= \text{Powerdissipationinsidetransistors} = [W] \\
 T_{hJ} &= \text{Junctiontemperature} = [^{\circ}C] \\
 T_{hA} &= \text{environmentaltemperature} = [^{\circ}C] \\
 R_{JC} &= \text{heatresistancejunctiontocase} = \left[\frac{K}{W}\right] \\
 R_{CH} &= \text{heatresistancecasetoheatsink} = \left[\frac{K}{W}\right] \\
 R_{thK} &= \text{maximumheatresistanceoftheheatsink} = \left[\frac{K}{W}\right] \\
 R_{thK} &= \frac{T_{hJ} - T_{hA}}{P_v} - (R_{JC} + R_{CH}) [24] \tag{2.12}
 \end{aligned}$$

As shown in equation 2.12 the only parameter to calculate the heat sink that is not a constant of the used parts, is the power dissipation inside the transistors. The calculation of the power dissipation is implemented in a MATLAB script shown in Attachment A. In chapter 4.2.3 is mentioned that in this Thesis two power amplifier are used which act as a pair. Because of that the MATLAB script calculates the Power dissipation on a pair of transistors. The actual power dissipation on one transistor is the half of it. MATLAB is plotting the following graph 2.8 it shows the voltage and the power dissipation on a pair of transistors in dependance of the current flowing through them.

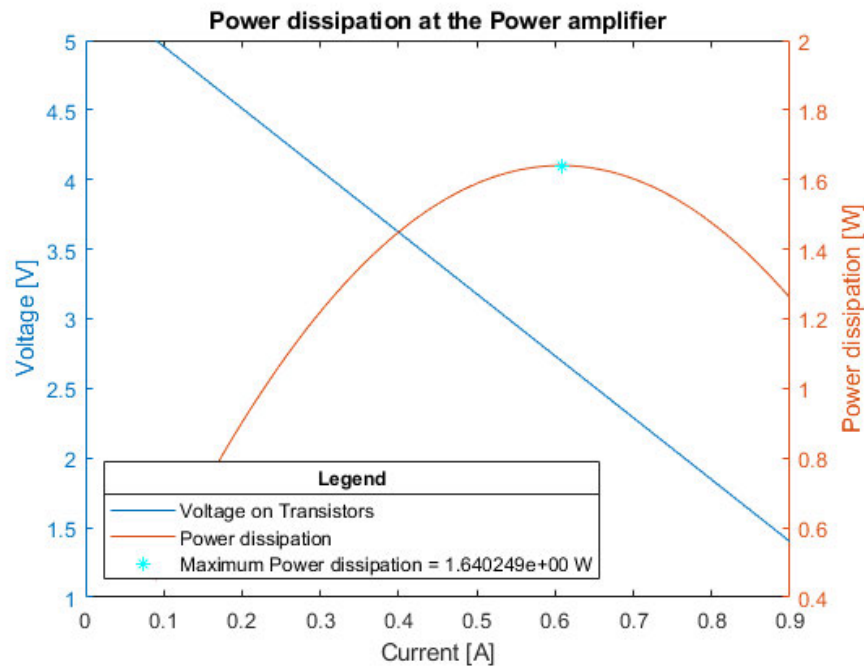


Figure 2.8.: MATLAB Plot Power dissipation over the Poweramplifiers transistor pairs

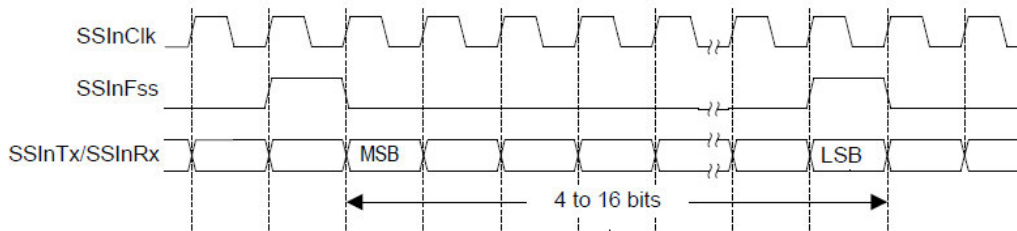
As shown in figure 2.8 the maximum power dissipation on a pair of transistor is  $P_{vx2} = 1.640249 W$ . This leads to a power dissipation per transistor of  $P_v = \frac{P_{vx2}}{2} = 0,8201245 W$ .

## 2.10. PCM3003

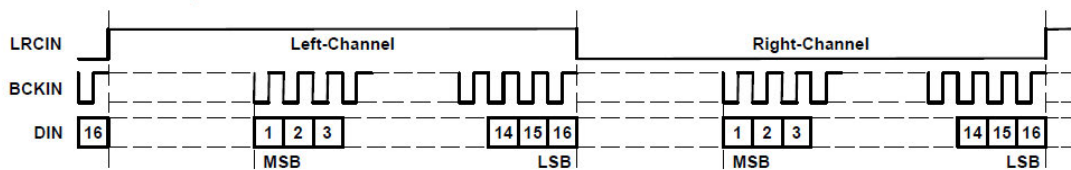
The PCM3003 is a stereo audio codec. It consists in two analog inputs, two analog outputs, a 20-Bit monolithic  $\Delta\Sigma$  ADC and a 20-Bit monolithic  $\Delta\Sigma$  DAC. To communicate with other systems the PCM3003 has a serial interface shown in chapter 2.11 figure 2.9(b). The LRCIN signal is the word clock but it also provides the information if the data on digital output is send by the left or by the right channel and it is the sample rate of the PCM3003. configuring the PMC3003 is possible by hardware, the sampling rate can be from  $4 kHz$  to  $48 kHz$ [25].

## 2.11. Codec serial Interface and TISSF

To be able to communicate with the audio codec the main controller and the codec have to use the same serial interface. The audio codec uses a serial interface special for digital audio signals (figure 2.9(b)[25]). A serial interface similar to the codec interface, that is provided by the main controller, is the TISSF (Texas Instruments Synchronous Frame Format) interface (figure 2.9(a)) [11].



(a) Diagram of a serial communication with TISSF [11]



(b) Diagram of a Serial communication with PCM Audio Interface [25]

Figure 2.9.: Comparison of a serial communication with TISSF and a serial communication with the PCM Audio Interface

As shown in figure 2.9 the difference between the both serial interfaces is the LRCIN/SS-InFSS signal. This difference is solved by a logic circuit described in chapter 4.2.2.2 and is developed in chapter 6.1.2.

## 2.12. MAX232

The MAX232 is a signal converter used to convert two UART signals into a RS232 signal. To do so the MAX232 has internal charge pumps to generate the RS232 signal voltage from the 5 V supply voltage. It also provides the possibility to convert incoming RS232 signals back into UART signals [26].

## 2.13. Logic ICs

Logic ICs are categorized in different temperature ranges and application fields, classes and types. A number code provides information about them and helps to differ between them. The structure of this is shown in the following tabular2.1 [2].

XX	-	YY	-	ZZ
Temperature range/Usage		class		type
54, 74, 84		H, HC, HCT, AHC, LV, LVC, ECL, LSL, BCT, ...		00, 01, 02, 03, 04, ...

Table 2.1.: IC number code structure [2]

In case of this Thesis 74LV and 74LVC type Logic IC are used. 74 means that it is a standard IC with a temperature range of  $0^{\circ}\text{C}$  to  $70^{\circ}\text{C}$ . LV is an abbreviation for Low Voltage. That means that this IC is able to be supplied by a voltage source  $1.65\text{ V} - 3.6\text{ V}$ . If it is an LVC IC it means that even if it is powered by a lower voltage it is tolerant to 5 V signals[2].

### 2.13.1. 74LV4040

The 74LV4040 is a 12-Bit asynchronous binary counter[27] that counts clock events on its CLK input. In this Thesis it is used as a clock divider.

### 2.13.2. 74LVC1G374

The 74LVC1G374 is a single D Flip-Flop with 3 state output. It puts the input value to the output if a clock event occurs on the clk input [28]. It is used to create a time delay in this Thesis.

### 2.13.3. 74LVC1G86

The 741G86 is a single XOR Gate with two inputs. It creates an high output value if only one of the two inputs has a high signal[29].

### 2.13.4. 74LVC125

The 74LVC125 is a quadruple bus buffer gate with 3 state output. It has to be enabled by pulling down the enable input to GND. If that is done the 74LVC125 displays the input value at the output. By supplying the 74LVC125 with a 5 V supply voltage it is able to convert a 3.3 V data signal into a 5 V data signal[30].

### 2.13.5. PLL

A PLL (Phase Locked Loop) is a regulator that regulates the phase of it's output signal to match with the phase of the input frequency. Following that the PLL also regulates its output frequency to match with the input frequency. By adding a frequency divider to the feedback input of the PLL it is possible to set up the output frequency higher then the input frequency (figure 2.10)[31].

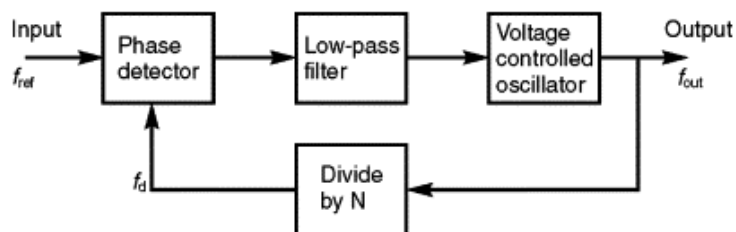


Figure 2.10.: Circuit diagram: Standard PLL Circuit[32]

The following equation is used to calculate the output frequency of the PLL(equation 2.13).

$$f_{out} = f_{ref} \cdot \frac{1}{N} [32] \quad (2.13)$$

As shown in figure 2.10 the PLL contains three sub parts. The Phase detector is a logic that detects a phase difference between the signal at the input of the PLL and the signal at the feedback input of the PLL. Following the phase detector a low pas filter is generating a low frequency (or a direct voltage) out of the pulsed signal from the phase detector. A VCO (Voltage Controlled Oscilator) is controlled by the output signal of the low pass and puts out a signal with afrequency depending on the signal voltage after the lowpass[33].

## 3. Requirements

As mentioned in the introduction (Chapter 1) the electronic guide dog is still under development. Following this, this chapter is a try to predict the requirements of systems used in the future which may not even be in the concept at now. Because the power supply for these systems is not a part of the MSA Board the following power supply requirements are only to run the MSA Board. Other parts of the future systems not known to day are the serial interfaces they communicate with, the reference voltage they need and the signal voltage they use. The electronic guide dog shall have an audio interface but not known today is which parts are used for it and how extensive it will be. No one knows how often the systems connected to the MSA Board will change. So connection to the MSA Board will have some requirements for it self. To be prepared to support all the solutions for the unanswered questions with the MSA Board the following requirements were defined. The requirements were defined by the fact that this project is build inside a vacuum cleaner (Chapter 1.2.2), the requirement to predict the future systems and some safety reasons.

### 3.1. Circuits

This subsection contains all requirements that have an effect on the part selection for each part of the MSA Board.

#### 3.1.1. Power Supply

These are the requirements made on the power supply for the MSA Board.

- To make the power distribution platform (mentioned in chapter 1.2.1) as cheap and uncomplicated as possible it is required to use standard supply voltages on the MSA Board.
- To adapt the MSA Board circuits into the surrounding systems, a supply voltage of 3.3 V and/or 5 V is required.
- It is required to support the possibility to measure the accumulator voltage with the main controller for safety reasons.



#### 3.1.2. Audio

This subsection contains the requirements for the audio parts in on the MSA Board. It is divided in the parts audio signal converter that is required to do an audio output from the main controller and the audio amplifiers to amplify the converters analog in- and output signals.

##### 3.1.2.1. Audio Signal Converter

- An audio signal converter is required to convert an analog microphone signal into a digital signal.
- An audio signal converter is required to convert a digital audio signal into an analog audio signal for an audio output.
- It is necessary that the audio converters are able to communicate with the main controller.

##### 3.1.2.2. Audio Amplifier

- The MSA Board requires an amplifier to amplify microphone signals before they enter the audio converter.
- The MSA Board requires an amplifier to amplify the audio signals from the audio signal converter for the audio output.
- To support a wide range of speakers the final stage of the audio amplifier used at the speakers has to be able to handle a load with a impedance of  $4\ \Omega$  or more [34].
- The final stage of the audio amplifier for the speaker will be the the biggest power consumer on the MSA Board and it is only required to do an audio output if it's necessary. Following that the final stage is required to be shut down if it's not used.

#### 3.1.3. Other Signal Converters

Aside from the audio part there are other systems which may require other signal voltages.

- To convert a UART signal with a level of  $3.3\ V$  into a RS232 signal a signal converter for two UART serial interfaces is required.
- To communicate with model-building parts, level converter from  $5\ V$  to  $3.3\ V$  and from  $3.3\ V$  up to  $5\ V$  are necessary [11].

#### 3.1.4. Connectors

As mentioned before there are a lot of different systems required to be connected to the MSA Board(Chapter 1.1). The following lists the connector requirements for already decided systems.

- To connect with the bottom side of the EK TM4C1294XL main controller, the MSA Board requires four 2 · 10 pin header [11].
- To connect with model-building parts, the compass module, the bluetooth module and for test pins other pin headers are required.
- The power supply and the audio signals should not be connected the wrong way, these jacks are required to have a wrong connection protection.

##### 3.1.4.1. Main Connectors

Most peripheral systems to the MSA Board aren't decided as mentioned before. Following this it is not known now how the connector look like. With that in mind the following requirements for the main connectors where defined.

- Because of the changes the electronic guide dog will undergo while its development it is required to be very easy to connect a new system onto the main connector.
- The main connectors have to withstand many connection changes.
- It is required that there is no complicated tools needed to connect something to the main connectors.
- The main connectors have to be mounted solid on to the MSA Board.

## 3.2. Board

This Requirements are valid on the whole Board and have to be applied to all previously mentioned subsystems of the EGD.

- The MSA Board should have a size of  $9\text{ cm} \cdot 12\text{ cm}$  to fit into the vacuum cleaner
- Each connection from the main controller to the outside has to be protected by a  $100\ \Omega$  Resistor to protect the in- and outputs against wrong use or high peak currents during switching operations.
- Each supply pin has to be supported with a  $10\ \mu F$  capacity and a  $100\ nF$  capacity to support the supply voltage during switching operations.
- Because of a lack of space and airflow, the power amplifier is required to send out not too much heat.
- It is required to leave space on the MSA Board to assemble the MSA Board into the vacuum cleaner.

#### 3.2.1. Supported Serial Busses

To get the right amount of pins on the main connector and be as flexible as possible with the MSA Board the following list of signals is required:

- Two I2C busses with two cascades each.
- Two SPI busses with two cascades each.
- Five PWM outputs.
- Two PWM inputs.
- Two interfaces for stepper motors.
- Three analog inputs.
- Five UARTs with two of them supporting the RS232 standard.
- A complete port of eight pins as digital I/Os.

## 4. Concept

This chapter contains a concept to realize the requirements defined in the previous chapter 3. In addition to the fundamentals of chapter 2 the concept is used to develop the MSA Board to fit into the requirements.

### 4.1. Chassis

To fit the until now biggest and already decided boards of the electronic guide dog (video processor, MSA Board and the main controller) inside the vacuum cleaner they get stacked onto each other to save space (figure 4.1).

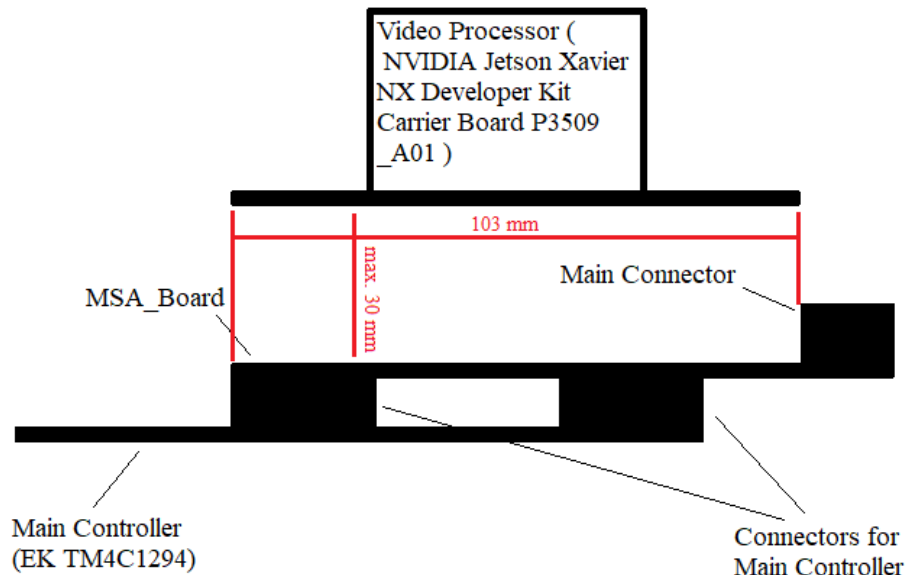


Figure 4.1.: Stacked boards with Video Processor, MSA Board and Main Controller

As shown in figure 4.1 the stacked boards shall not be mounted too high. This results in a maximum height of 30 mm for each part underneath the video processor board. The Video Processor itself has a length of 103 mm [35]. To get an area to place the main connectors the MSA Board is required to have a length of 120 mm. Not shown in figure 4.1 is the attachment of the video processor on the MSA Board. This attachment is a 3D print that is not part of this bachelor thesis and had not been decided until the end of the thesis. The main controller is attached upside down from underneath to the MSA Board by its connectors. Because of this, the connectors for the Main Controller [11] have to be mirrored to the bottom side of the MSA Board.

Figure 4.2 shows a possible board. The marked areas in the left corners are intended to be left free of electrical parts of the MSA Board. These free areas are intended to be used to slide into attachment rails to attach the MSA Board into the vacuum cleaner. The length of the sliding areas had not been defined and assumptions need to be made. On the right side of the MSA board a bigger area is marked. This area is not covered by the Video Processor and provides the necessary space to place the main connectors. Two drill holes in the main connector area are marking another part of the MSA Board attachment. These holes shall have a diameter of  $2.5\text{ mm}$  to put M2 screws through them. The exact location of this holes will be defined in a later step of this thesis.

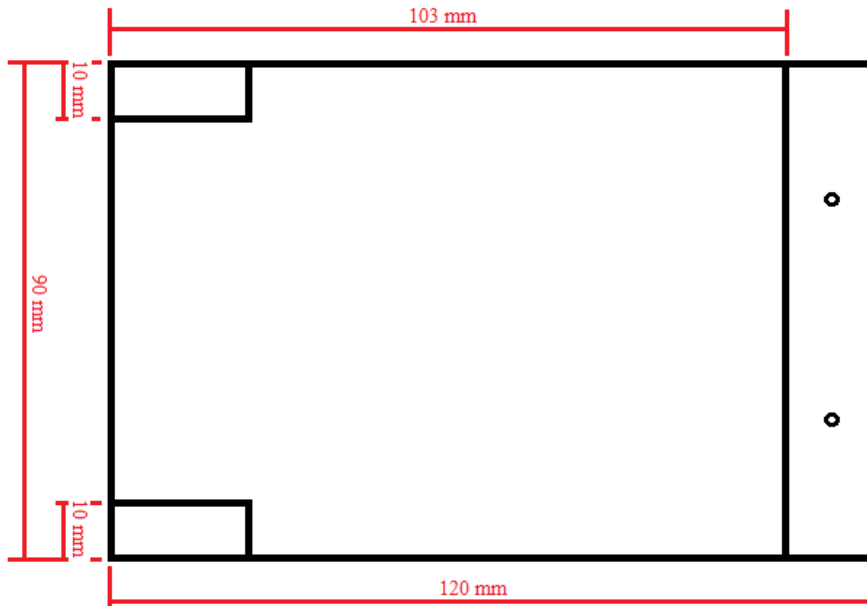


Figure 4.2.: Top view on the MSA Board concept

## 4.2. Electronic Systems

The following texts are describing concepts for the electronic subsystems. It is divided into the subsystems power supply, audio signal converter and its sub sub systems, the audio amplifiers, other signal converters and the connectors.

### 4.2.1. Power Supply

As mentioned before, the MSA Board needs different supply voltages (Chapter 3.1.1). The main controller is powered by a  $5\text{ V}$  supply [36] provided by the MSA Board. With a TPS73733 the EK-TM4CXL generates a  $3.3\text{ V}$  supply voltage out of the  $5\text{ V}$  from the MSA Board. The TPS73733 has a maximum current output of  $1\text{ A}$  and is used to supply the  $3.3\text{ V}$  systems on the MSA Board [36, 37]. It is possible to leave the main controller on the MSA Board while programming it because of a TPS2052B that is placed at the USB input of the EK-TM4C1294XL. This TPS2052B is a power distribution IC that prohibits a short cut between the USB supply and the MSA Board supply [36, 38].

### 4.2.2. Audio signal converter

To convert an analog audio signal coming from a microphone into a digital signal and a digital signal coming from the main controller into an analog audio signal an audio codec is needed. In this Thesis the PCM3003 is used, because it is powered by a supply voltage of 3.3 V, it is configurable by hardware so it doesn't need a control bus and its serial interface is similar to a SPI or TISSF (figure 2.9) interface [11, 25]. To supply the audio codec with the required clock signals (SYSCLK, BCKIN, LRCIN [25]) two concepts were designed (chapter 4.2.2.2 and chapter 4.2.2.1).

#### 4.2.2.1. PLL concept

The PLL concept to create the required clock signals for the PCM3003 uses the TM4C1294 as Master for the serial connection and as clock source. To convert the signals of the controllers serial interface (figure 2.9(a)) into the serial interface of the PCM3003, the SSInFSS signal needs to be converted into the LRCin signal of the codecs serial interface (figure 2.9(b)). To do so the SSInFSS signal is connected to the CLK input of a 74LV4040 counter the output signal on pin 9 is the LRCin signal [27]. The SSYSCLK clock signal is created by using a PLL and another counter as frequency divider (chapter 2.13.5).

#### 4.2.2.2. Quartz concept

An alternative concept to the PLL concept is the Quartz concept. The Quartz concept uses an quartz oscillator to generate the system clock SYSCLK of the PCM3003 (12.288 MHz [25]). With a 74LV4040 [27] counter the output frequency of the quartz oscillator is divided into the bit-clock SSInCLK/BCKIN and the word clock/sample rate LRCIN. The TM4C1294 is running in slave mode in this concept. To generate the SSInFSS signal out of the LRCIN signal and the BCKIN signal, a series of an 74LVC1G374 [28] D Flip-Flop and a 74LVC1G86 XOR Gate is used [29]. By connecting the LRCIN signal to the input of the D Flip-Flop and the BCKIN signal to the clock input of the 74LVC1G374 [28] a LRCIN signal is generated that has a delay of one BCKIN signal cycle. If these both signal (LRCIN and LRCIN delayed) are connected to both inputs of the XOR Gate. Doing this generates the wanted SSInFSS signal on the output at the Output of the XOR gate (74LVC1G86 [29]) (Figure 2.9).

### 4.2.3. Audio amplifier

This chapter describes a concept for the audio amplifiers required to amplify the microphone signal as input for the PCM3003 and to amplify the analog output signals of the PCM3003 for the speaker. The microphone (EMY-63M/P [39]) output connected to the amplifier via a transmission transistor (Chapter 2.3). Because of the high resistance of the PSM3003s analog input [25] a non-inverting amplifier (Chapter 2.5) without the a final stage is used as amplifier. The amplified signal is connected to the PCM3003 via a RC low pass (Chapter 2.2).

To amplify the the analog output signal of the PCM3003 the signal is low pass filtered at first (Chapter 2.2). After that the analog output signal is connected to a non inverting operational amplifier (Chapter 2.5) via an transmission capacitor (Chapter 2.3). The amplified signal is connected to two other operational amplifiers as impedance

converter. One of these operational amplifiers has a amplifier factor of 1 and the other one has a amplifier factor of -1 (Chapter 2.6). Both signals are connected to a final stage (Chapter 2.7) each. By connecting the speaker between the both final stages the complementary signals getting subtracted and the amplitude of the hearable audio output is doubled [1] (Appendix C).

### 4.2.4. Other signal/level converters

Model-building parts and many other systems which may be used on the EGD project uses a signal voltage of 5 V. The main controller uses a signal voltage of 3.3 V [11]. To convert a 3.3 V signal into a 5 V signal two quadruple bus buffer gates (74LVC125 [30] Chapter 2.13.4) are used.

Another often used standard serial interface is the RS232 bus. As mentioned before (Chapter 3.2.1). To convert two 3.3 V UART signals into a RS232 signals and two RS232 signals back into UART signals, a MAX232 signal converter is used(2.12 [26]).

### 4.2.5. Connectors

As mentioned before there are many requirements for the connectors on the MSA Board 3.1.4.1. The main controller needs for  $2 \cdot 10Pin$  pin headers to connect to the MSA Board [40]. Also connected by pin headers are the compass module, the Bluetooth module and the model-building parts because they are already decided and they will be not changed any more. If the model building parts are changed the left over connectors can be used for voltage references and the 2.54 mm grid of the pin headers fits on the standard model-building connectors (tested) [41].

The power supply and the audio signals are connected to their peripherals and the power supply via a header of type MSTB. These connectors are easily available, in many different, can't be connected the wrong way round and can support a high current [42].

For the main connectors PTSM Fixed Terminal Blocks are used. Because of their small grid of 2.5 mm many output pins can fit into the main connector section on the board (Figure 4.2). The PTSM connectors are opened by pressing in a screw driver and can handle different wire cross sections. A plug is not necessary the wires only need to be uninsulated to be connected. The stability on the board of these connectors is realized by a double row of pins [43].

## 5. Used Tools

This chapter contains a list of software and tools used for this bachelor thesis.

Hardware / Software	Usage
EK-TM4C1294XL Development Board	Main Controller
HC-05	Bluetooth module
HMC5883L	Compass Module
SDS1204X-E	Oscilloscope
DG832	Function Generator
BT-305	Test Power Supply
Microsoft Paint	sketch software
EAGLE 7.7.0	Circuit & Board Layout Editor
Overleaf.com	Latex Editor
LibreOffice Calc	table editor
MATLAB R2021a Update5	calculator

Table 5.1.: Used Hard- and Software

### **EK-TM4C1294XL Dvelopment Board**

The EK-TM4C1294XL in a development board is used as main controller in the EGD project. It provides many different interfaces on its four connectors and can run on a clock frequency up to  $120\text{ MHz}$  [44].

### **HC-05**

For Bluetooth communication with external hardware a HC-05 Bluetooth module is mounted on the MSA Board. The HC-05 can act as an master or a slave in Bluetooth communication and is connected to the MSA Board by UART.

### **HMC5883L**

To detect direction and angle of the electronic guide dog the HMC5883L compass module is mounted on the MSA Board. It communicates with the main controller using an I2C interface [45].

### **SDS1204X-E**

The SDS 1204X-E is a oscilloscope [46]. It is used to measure and check the signals used on the electronic guide dog.

### **DG832**

The DG832 is a waveform generator that can generate an output signal in different frequencies, forms and voltages [47]. It is used to simulate signals needed by the electronic guide dog.



### **BT-305**

The BT-305 is a labor power supply with a adjustable current limit. It is used to test the circuits before putting them on the MSA board [48].

### **EAGLE 7.7.0**

EAGLE is a software toll to draw circuit diagrams. It is possible to design a board layout out of the circuit diagrams in EAGLE. To do so EAGLE contains a library with many different parts used in the electronic development.

### **Overleaf**

Overleaf is a website that provides a LATEX editor. IT is possible to share the link of a project to write together with colleaques.

### **LibreOffice Calc**

LibreOffice Calc is a tabular calculation tool used to create material and pin lists.

### **MATLAB**

MATLAB is a Tool used to calculate many different things and plot graphs of them.

### **Microsoft Paint**

Microsoft Paint is a software used to sketch concept sketches.

## 6. Development

This chapter describes the development process to create the MSA Board using the requirements, the concept and the fundamentals. Following this, this chapter is putting together the previous work until now to create the MSA Board. The chapter is divided in a Circuit section where the Circuit diagrams are developed and a Board section where the Board layout is developed.

### 6.1. Circuit

In this section of the chapter the Circuit diagrams of the MSA Board are developed. It is divided in a PCM3003 part, a part where the different clock signals are created, a speaker amplifier part, a microphone amplifier part, a part where the accumulator voltage is measured and the signal converter parts.

#### 6.1.1. PCM3003

This part of the thesis describes the circuit diagram around the PCM3003 audio codec. It contains the configurations of the PCM3003 and the both low pass filters at the analog input and the analog output of the PCM3003

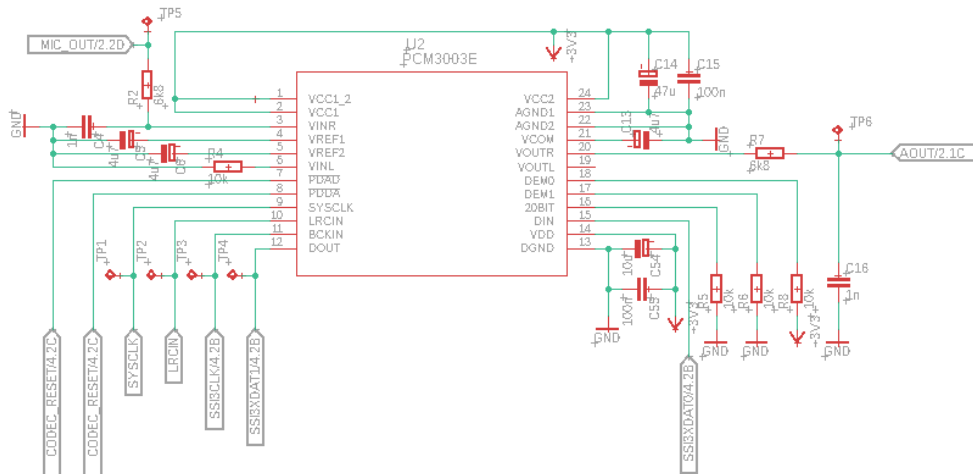


Figure 6.1.: Circuit diagram of the PCM3003 with low passes on analog in- and output [25]

Figure 6.1 shows the PCM3003 with its stabilizing capacitors for the analog and digital voltage supply ( $C_5$ ,  $C_6$ ,  $C_{13}$ ,  $C_{14}$ ,  $C_{15}$ ,  $C_{54}$  and  $C_{55}$ ). It is configured by the resistors  $R_5$ ,  $R_6$  and  $R_8$  to run in 16 Bit mode and de-emphasis disabled. The option to shut down the ADC or DAC unit inside the PCM3003 is operated by the main controller [25]. TP1 - TP6 are test pins to be able to check the PCM3003 signals on the MSA Board.  $R_2$  and  $C_4$  are forming a low pass. That shall have a cut off frequency of over  $20\text{ kHz}$  [13]. Starting with capacity of  $1\text{ nF}$  for  $C_4$  and a cut off frequency of over  $20\text{ kHz}$  Equation 2.2 is used to calculate a resistor  $R_2 = 7.9577\text{ k}\Omega$ . To fit the resistor into the E12 series a resistance of  $6.8\text{ k}\Omega$  is used [49]. The capacity of  $1\text{ nF}$  and the resistor series E12 are selected because they are cheap and available in many packages at the most distributors for electronic parts.

### 6.1.2. Generate Clock Signals

The purpose of this chapter is to describe the development of the two concepts to generate the signals for the serial audio interface.

#### 6.1.2.1. PLL

This part of the chapter contains the circuit diagram of the PLL circuit described in Chapter 4.2.2.1.

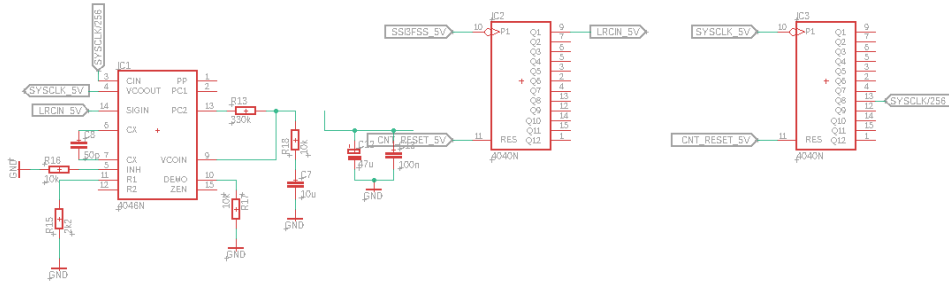


Figure 6.2.: Circuit diagram of the PLL concept to generate the necessary signals [27, 33, 50]

The PLL is configured by  $R_{15}$ ,  $R_{16}$ ,  $R_{17}$  and  $C_8$  using Resource [33] to an output frequency of  $12,288\text{ MHz}$  [25].  $R_{13}$ ,  $R_{18}$ ,  $C_7$ ,  $C_{12}$  and  $C_{13}$  are used to create a second order RC low pass using Resource [50].

## 6.1.2.2. Quartz

The circuit diagram shown in the following Figure 6.3 is described in Chapter 4.2.2.2.

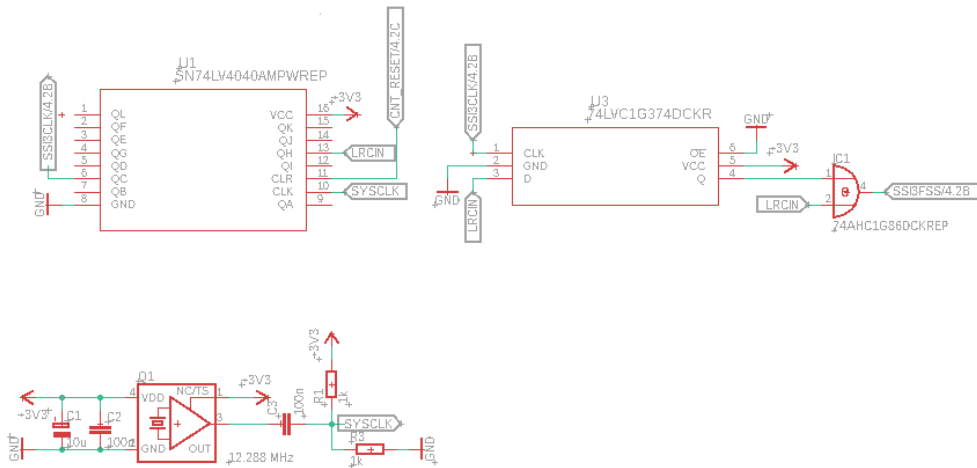


Figure 6.3.: Circuit diagram of the Quartz concept to generate the necessary signals [51, 27, 28, 29]

In addition to the circuit described in Chapter 4.2.2.2 the circuit shown in Figure 6.3 contains a transmission network formed by  $R_1$ ,  $R_3$  and  $C_3$ . It is used to set the offset voltage of the clock signal generated by the quartz oscillator to  $\frac{3.3V}{2}$  to be safely detected by the following 74LV4040 and the PCM3003 [25, 27]. The resistors are set to a value of  $1k\Omega$  because if someone is checking the clock signal with an oscilloscope the internal resistance  $1M\Omega$  is influencing the measurement if a much higher resistance is used [46].

## 6.1.3. Speaker amplifier

This part of the Chapter contains the development of the speaker amplifier containing the creation of the reference voltage, the pre-amplifier, and the final stage.

## 6.1.3.1. Reference Voltages

The reference Voltage of the speaker amplifier has to be  $2.5\text{ V}$  to maximise the amplitude the output signal could have.

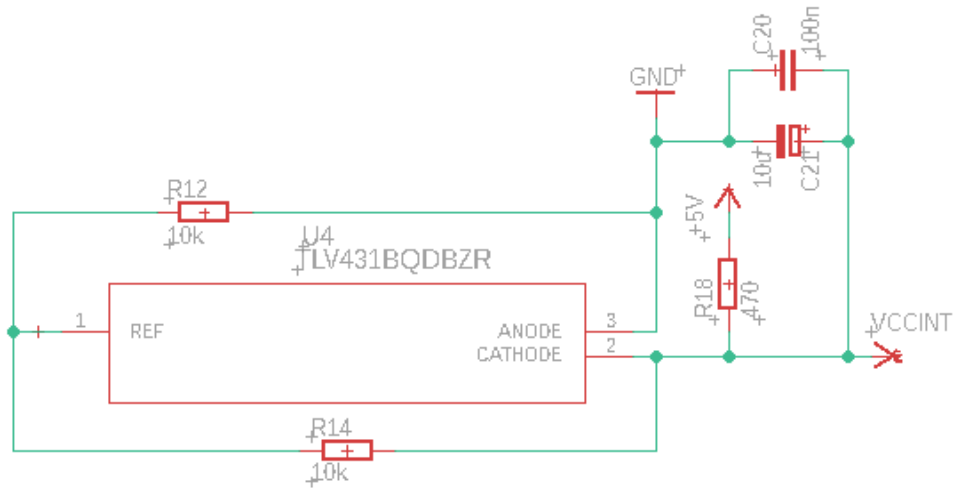


Figure 6.4.: Circuit diagram to create the reference Voltage of the Speaker amplifier [23]

As shown in Figure 6.4 the capacitors  $C_{21}$  and  $C_{20}$  are used to stabilize the reference voltage.  $R_{18}$  limits the current flowing through the TLV431 circuit. The output voltage of the TLV431 is the reference voltage for the speaker amplifier and is defined by Equation 2.10. Starting with a resistor  $R_{14} = 10\text{ k}\Omega$  and a desired output voltage of  $2.5\text{ V}$  Equation 2.11 is used to calculate  $R_{12} = 10\text{ k}\Omega$ . A start resistor of  $10\text{ k}\Omega$  is selected because a  $10\text{ k}\Omega$  resistor is part of the E12 series, the flowing current is limited to a small current and the range of other resistor available to complete a voltage divider is wide in each direction.

### 6.1.3.2. Pre-Amplifier

The pre-amplifier is doing the voltage amplification in the speaker amplifier. It is a non inverting operational amplifier as described in Chapter 2.5.

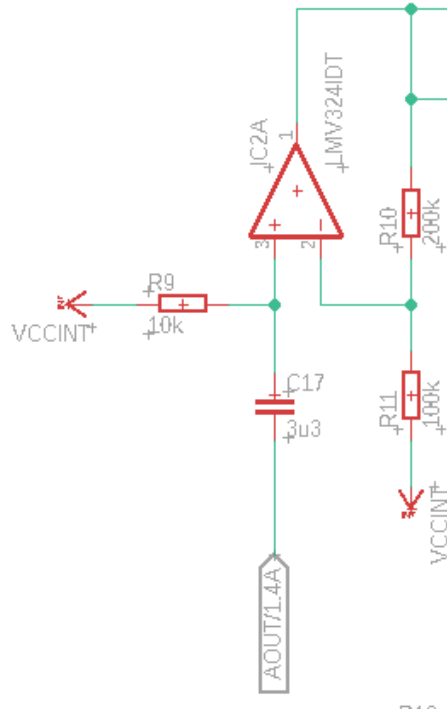


Figure 6.5.: Circuit diagram of the Speaker amplifiers pre-amplifier

As shown in Figure 6.5  $C_{17}$  a transmission capacitor building a high pass with  $R_9$ .  $R_9$  also sets the reference voltage to the non inverting input of the operational amplifier. Its value is selected to  $10\text{ k}\Omega$  because the flowing current is small, it is part of the E12 series and the created high pass has a cut off frequency  $f_g$  of  $4.8\text{ Hz}$ .

To calculate the amplification factor of the pre-amplifier the low pass shown in Figure 6.1 consisting of  $R_7$  and  $C_{16}$  and the high pass mentioned before consisting of  $R_9$  and  $C_{17}$  have to be taken into account. To calculate the maximum amplitude after the both filters a MATLAB script is written shown in Appendix D. The MATLAB script plots the graph shown in Figure 6.6. It calculates a maximum amplitude of  $0.579315\text{ V}$  at frequency of  $336\text{ Hz}$  after the filters.

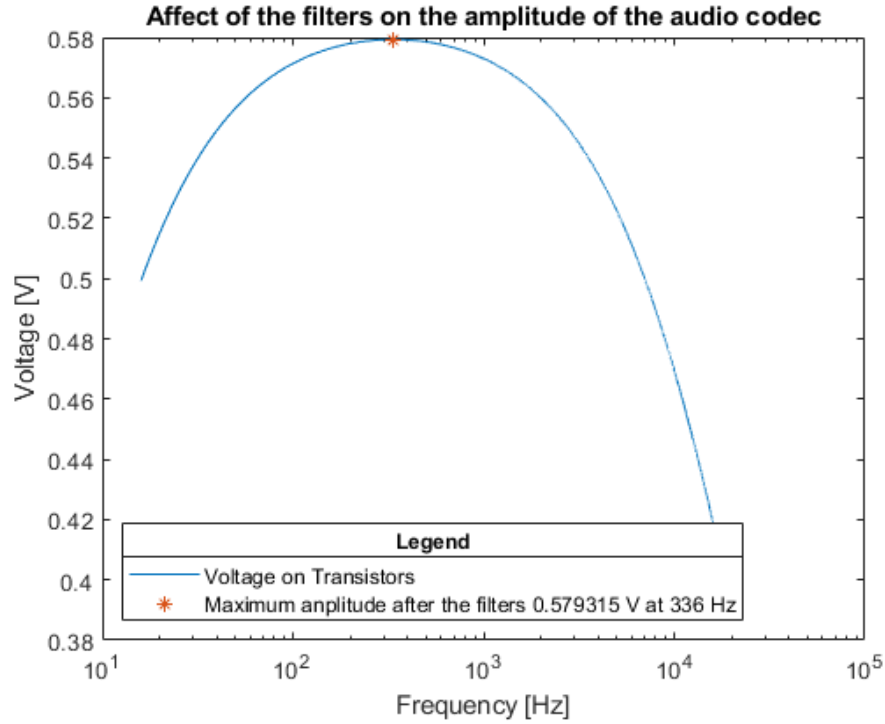


Figure 6.6.: MATLAB Plot of the Codecs output amplitude after filters

The calculated amplitude after the filter is used to calculate the amplification factor of the pre-amplifier. Starting with the calculated maximum amplitude, a maximum output amplitude of  $1.8\text{ V}$  and a resistor  $R_{11} = 100\text{ k}\Omega$  using Equation 2.6 and Equation 2.7, a amplification factor of 3.1071 and  $R_{10} = 200\text{ k}\Omega$  is calculated. The maximum output amplitude of the speaker amplifier is calculated by the following Equation 6.1.

$$U_{out,max} = \frac{U_{supply}}{2} - U_{BE} \quad (6.1)$$

### 6.1.3.3. Final Stage

The final stage of the speaker amplifier is developed using Appendix C [1]

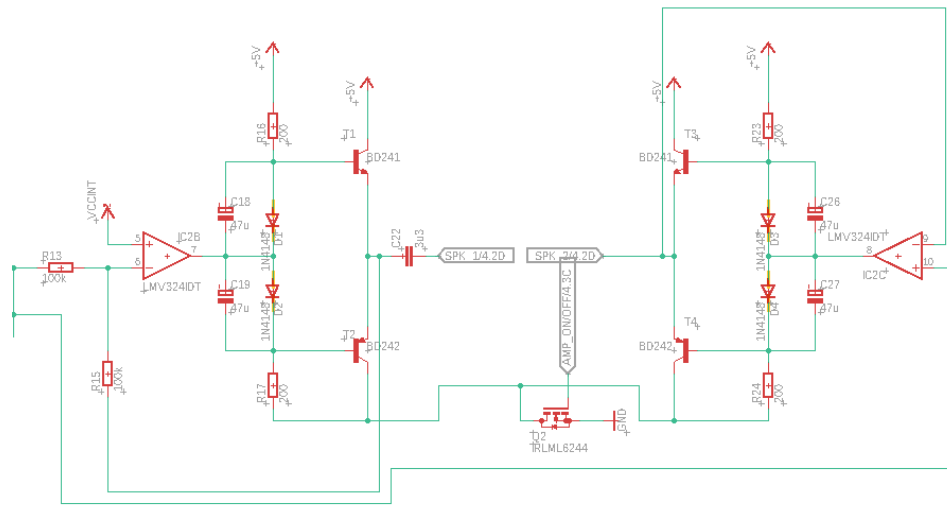


Figure 6.7.: Circuit diagram of the final stage of the Speaker amplifier [1]

As shown in Figure 6.7 the final stage consists of  $R_{13}$  and  $R_{15}$  forming an inverting amplifier (amplification factor = -1) with IC2B followed by the current amplifier described in Chapter 2.7. The other parts in this Figure, except for  $Q_2$ , are used to mirror this with a non inverting amplifier (amplification factor = 1). If  $Q_2$  is locked its high resistance shuts down the final stage as ordered in Chapter 3.1.2.2. Used as power transistors are BD241C and BD242C transistor because of the high current they can handle [20].

### 6.1.4. Microphone Input and Amplifier

This part of the chapter contains the description of the development of the microphone amplifier shown in Figure 6.8.

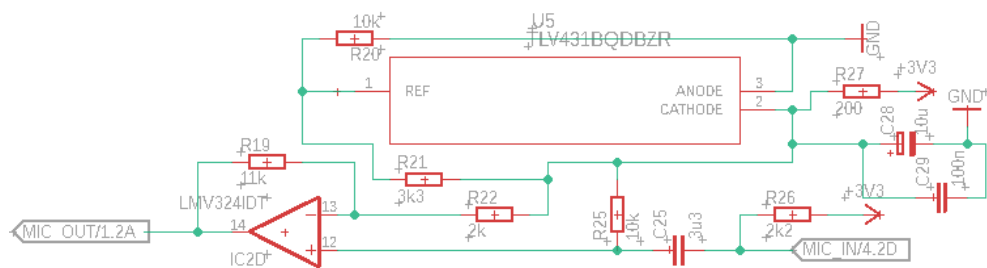


Figure 6.8.: Circuit diagram of the Microphone amplifier



Resistor  $R_{26}$  is part of the microphone circuit defined in the microphone data sheet [39].  $C_{25}$  is another transmission capacitor used to set up the microphone signal on to the voltage offset used by the PCM3003 [25] with  $R_{25}$ .  $R_{27}$  is used to limit the current in this TLV431 circuit [23]. The resistors  $R_{20}$  and  $R_{21}$  are used to define the output voltage of this TLV431 circuit. Starting with  $R_{20} = 10\text{ k}\Omega$  and a desired output voltage of  $1.65\text{ V}$  resistor  $R_{R21}$  is calculated by using Equation 2.11. The offset is half of the supply voltage of  $3.3\text{ V}$  and so it is possible to maximize the output amplitude of the microphone amplifier. IC2D,  $R_{R19}$  and  $R_{22}$  are forming another non inverting amplifier. To calculate the amplification factor of the microphone amplifier, a reference input signal is required. Because of a lack of reproducible loud traffic noises, a hand clap in a distance of  $10\text{ cm}$  to the microphone is used as a reference signal. It is measured with an oscilloscope and shown in the following Figure 6.9

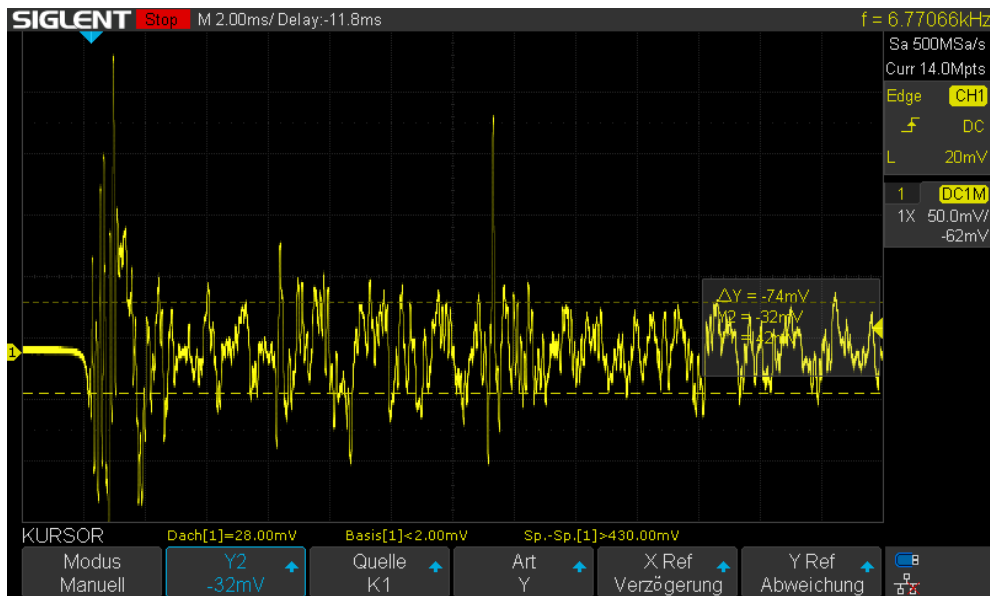


Figure 6.9.: Oscilloscope measurement of a hand clap in a distance of  $10\text{ cm}$

As shown in Figure 6.9 the amplitude of the clap signal reaches a voltage of nearly  $250\text{ mV}$ . Starting with an input amplitude of  $250\text{ mV}$ , a output amplitude of  $1.65\text{ V}$  and resistor  $R_{22} = 2\text{ k}\Omega$  by using Equation 2.6 and Equation 2.7 a maximum amplification Factor of 6.6 is calculated. By selecting an  $R_{19} = 11\text{ k}\Omega$  the amplification factor is limited to 5.5 for safety reasons to protect the PCM3003 [25].

### 6.1.5. Heat Sink

This chapter is using Chapter 2.9 to calculate the maximum heat resistance the heat sink could have. Starting with the data sheet of the power transistors [20] and the data sheet of the mica plate between the transistor and the heat sink [52]. Using these facts the parameters for Equation 2.12 are defined as followed:

- $P_v = 0.8201245 W$
- $T_{hJ} < 125^\circ C$  [20]
- $T_{hA} = 25^\circ C$
- $R_{JC} = 3.125 K/W$  [20]
- $R_{CH} = 1.2 K/W$  [52].

This results in a maximum heat resistance of  $117,61 K/W$  is calculated. In this Thesis a heat sink with a temperature resistance of  $25.9 K/W$  is used [53].

### 6.1.6. Accumulator Voltage Measurement

In this part of the chapter the development of a voltage divider to measure the accumulator voltage is described. The voltage divider is necessary to protect the analog input of the main controller [11] and is shown in Figure 6.10.

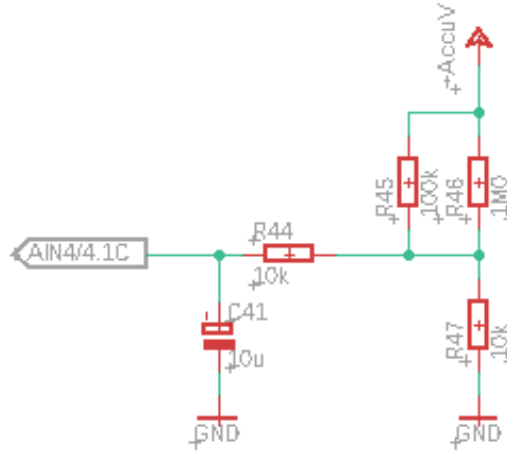


Figure 6.10.: Circuit diagram of the circuit to measure the accumulator voltage

As shown in Figure 6.10 is based on  $R_{47}$  with a value of  $10 k\Omega$  again. The other half of the voltage divider is formed by the parallel circuit of  $R_{45}$  and  $R_{46}$ . A total resistance of a parallel circuit of two resistors is calculated by the following Equation 6.2.

$$R_{total} = \frac{1}{\frac{1}{R_{45}} + \frac{1}{R_{46}}} \quad [54] \quad (6.2)$$

If one of the Resistors is decided the other one is calculated by Equation 6.3.

$$R_{46} = \frac{1}{\frac{1}{R_{total}} - \frac{1}{R_{45}}} \quad (6.3)$$

To calculate the values of voltage divider the maximum voltage of the Accumulator has to be known. The vacuum cleaner has a seven cell Lithium Ion accumulator inside [12, 55]. Those cells have loading process cut off voltage of  $4.1\text{ V}$  to  $4.2\text{ V}$  [56]. Adding the single cells to gather in a serial connection the total cut off voltage of the seven cell accumulator is  $7 \cdot 4.2\text{ V} = 29.4\text{ V}$ . To get a output voltage of the voltage divider smaller  $3.3\text{ V}$  [11] at a input voltage of  $29.4\text{ V}$  the total resistance is calculated (Equation 2.4 and set to be  $90\text{ k}\Omega$  for safety reasons and to fit the resistor into the E12 series. Starting with  $R_{45} = 100\text{ k}\Omega$ ,  $R_{46}$  is calculated to have a value of  $900\text{ k}\Omega$  using Equation 6.3.  $R_{45}$  is decided to have a value of  $100\text{ k}\Omega$  because it is the next resistance bigger then  $90\text{ k}\Omega$  in the E12 series. Following that the resistor  $R_{46}$  is define to have a value of  $1\text{ M}\Omega$ . Using the previous mentioned resistor values is resulting in a output voltage of the voltage divider of  $3.234\text{ V}$  at a input voltage of  $29.4\text{ V}$  using the Equation 2.3 and Equation 6.2.  $R_{44}$  and  $C_{41}$  are forming a low pass used to stabilize the output voltage of the voltage divider.

### 6.1.7. MAX232

The following is a circuit diagram to run the MAX232 signal converter, that converts a UART signal into a RS232 signal (Figure 6.11). It is developed using the data sheet of the MAX232 [26].

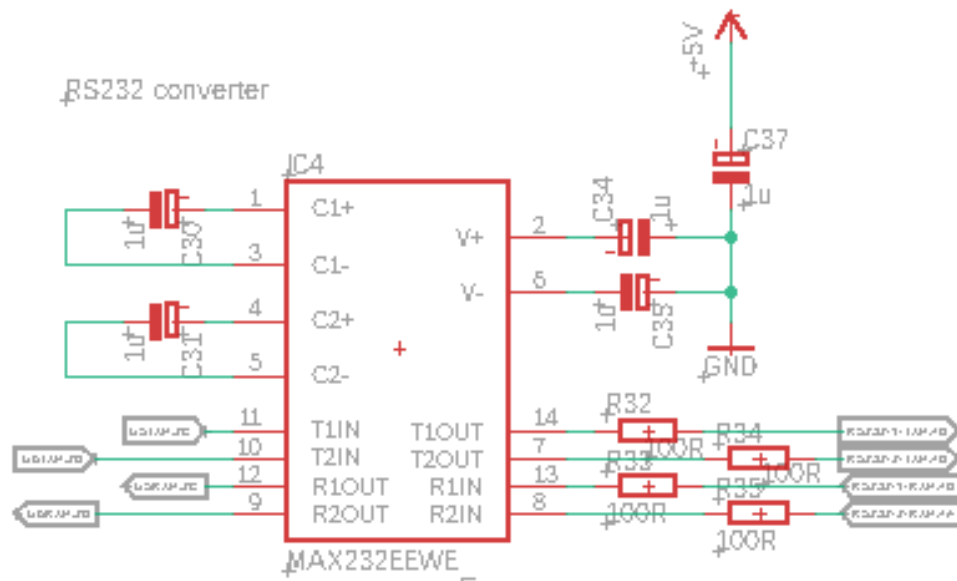


Figure 6.11.: Circuit diagram of the MAX232 [26]

Also shown in Figure 6.11 are the resistors  $R_{32}$ ,  $R_{33}$ ,  $R_{34}$  and  $R_{35}$  with a value of  $100\ \Omega$  each to protect the in- and outputs of the MAX232 against high current peaks during switching operations.

### 6.1.8. Signal Converter

This chapter part contains the signal converter circuit to convert a 3.3 V signal into a 5 V signal and the other way round. For this purpose two 74LVC125 quadruple bus buffers are used [30]. The circuit diagram shown in Figure 6.12 is developed using the data sheet of the 74LVC125 [30].

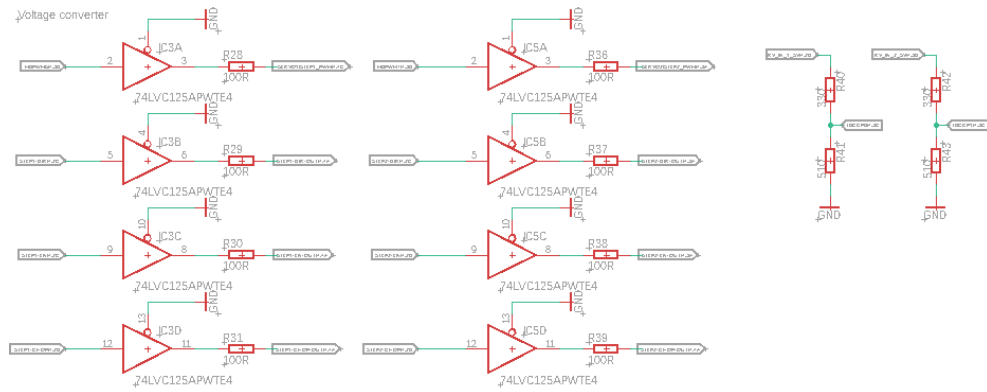


Figure 6.12.: Circuit diagram of the Signal converters [30]

The resistors  $R_{40}$ ,  $R_{41}$ ,  $R_{42}$  and  $R_{43}$  are forming voltage dividers. They are calculated using the Equations 2.3 and 2.4 and selected to fit into the E12/E24 series [49]. As shown in figure the values of are relatively low compared with other resistors in this thesis in order to support higher signal frequencies.

### 6.1.9. Connectors

The circuit diagram of the connectors of the MSA Board is described in the Chapter 4.2.5 and defined in Chapter 3.1.4. It is shown in Appendix E (Page 61). The cascades for the SPI and I2C bus systems are created using SPI and I2C data sheets [57, 58].

## 6.2. Board

Before designing the board layout of the MSA Board, a  $100\ \Omega$  resistor is added to every in and output of the main controller to protect it against high peak currents during switching operations. In addition to that each supply pin gets stabilized with a  $10\ \mu F$  and a  $100\ nF$  capacitor(Appendix E Page 61).

Also shown in Appendix E is that the quartz oscillator concept has made it onto the board because a proof of concept test shows the quartz concept runs more stable than the PLL circuit and it generates the necessary clock frequencies more precisely.

The board layout is created using an article about the width of the used wires [59], an article about the distance between the wires [60], an EAGLE FAQ [61], three design rule documents [62, 63, 64] and the board manufactures layout design rules [65]. The circuit diagrams resulting from this chapter are shown in Appendix E. Appendix F contains the created board layouts of all four Layers of the MSA Board. A list of the used materials on the MSA Board is located in Appendix G. The list of used pins on the EK-TM4C1294XL is located in Appendix H and the list of pins on the main connector is located in Appendix I.

## 7. Proof of Concept

This chapter provides some tests done to prove the concept. The tests described in this chapter are only a proof of concept. Some of the parts used to run these tests are not the same as in the actual MSA Board. Because of the differences in some components values, the shown signals and voltages may not be exactly conform to the desired values. A difference in values of some components occurs because of the use of components available at that moment that are not exactly the same as they were used later in the development. Some test like the test of the voltage divider to measure the accumulator voltage or the shut down function of the final stage are not even recorded in here. The tests shown in this chapter are the proof of concept of the microphone amplifier, the speaker amplifier, the circuits to run the PCM3003 the MAX232 and the test of the 74LVC125. To measure the figures in this chapter a SDS1204X-E four channel oscilloscope is used and the input signals are generate by a DG832 function generator [46, 47].

### 7.1. Microphone Amplifier

The Figure 7.1 shows the amplification of the microphone amplifier.

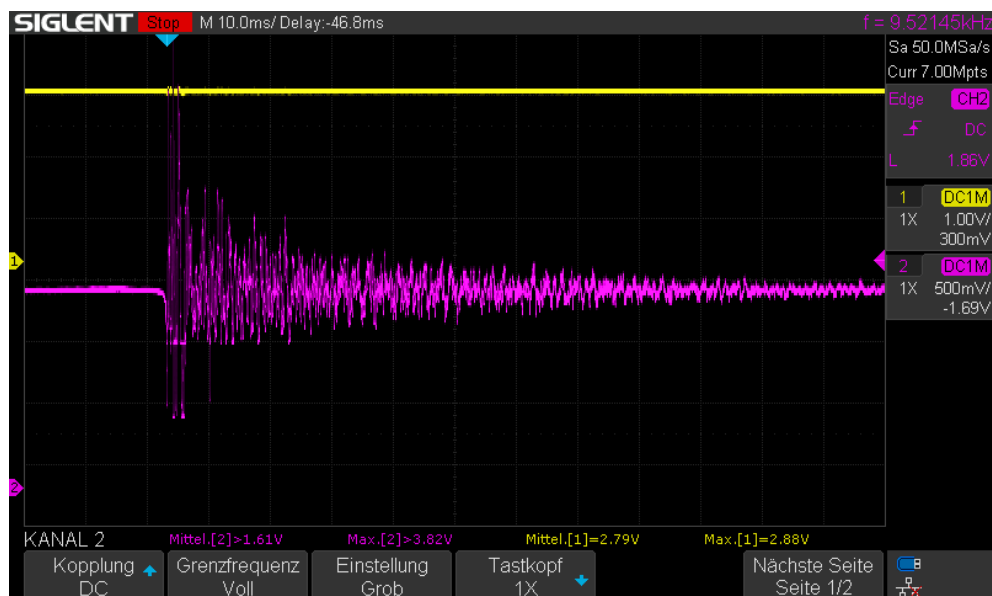


Figure 7.1.: Oscilloscope picture of a hand clap amplified by the microphone amplifier

As seen in the previous Figure 7.1 the amplifier is working as it should but the amplification factor is too high because the resistors used in this test to define the amplification factor are not the calculated ones but resistors available at that moment. The yellow graph shows the microphone signal before amplification ( $1\text{ V/div}$ ) and the pink graph shows the the hand clap signal after being amplified by the microphone amplifier.

## 7.2. Speaker Amplifier

This part of the chapter is showing the signals surrounding the speaker amplifier in Figure 7.2.

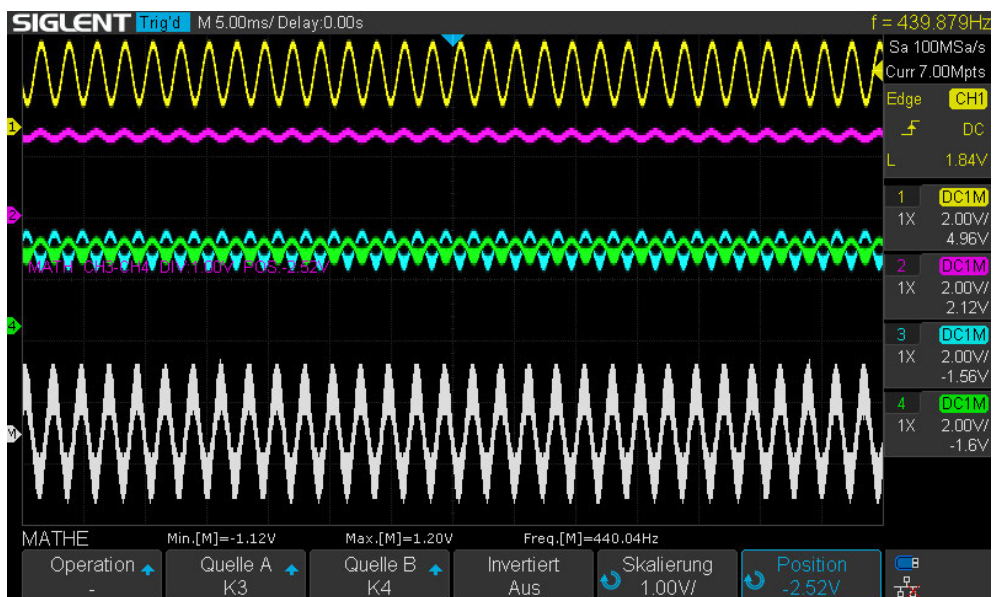


Figure 7.2.: Oscilloscope picture of a sinus signal and a  $4\ \Omega$  Speaker

The input signal (yellow  $2\text{ V/div}$ ) is getting filtered and is set to an offset of  $2.5\text{ V}$  (pink  $2\text{ V/div}$ ). After that the signal is amplified (green  $2\text{ V/div}$ ) and a complementary signal is produced (blue  $2\text{ V/div}$ ). The speaker is running on the green and the blue graph. That results in the graph plotted on the white math channel ( $2\text{ V/div}$ ).

## 7.3. PCM3003

The following both parts of this chapter are proofing the two concepts to create the clock signals for the PCM3003 [25].

## 7.3.1. PLL

The following Figures 7.3 and 7.4 are plotting the graphs of the PCM3003 signals produced by the PLL concept described in Chapter 4.2.2.1.

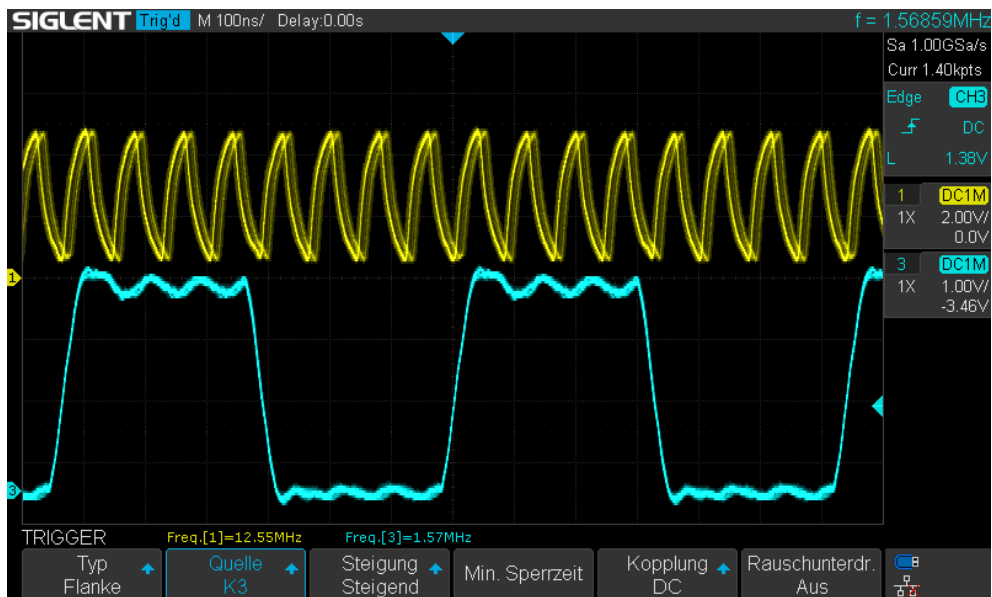


Figure 7.3.: Oscilloscope picture of the System clock signal created by the PLL from the bit clock

The previous Figure 7.3 shows the System clock signal (yellow  $2\text{ V/div}$ ) generated from the Bit clock signal (blue  $1\text{ V/div}$ ) using the PLL. As seen in Figure 7.3 the system clock signal is instable and it is effecting the bit clock signal

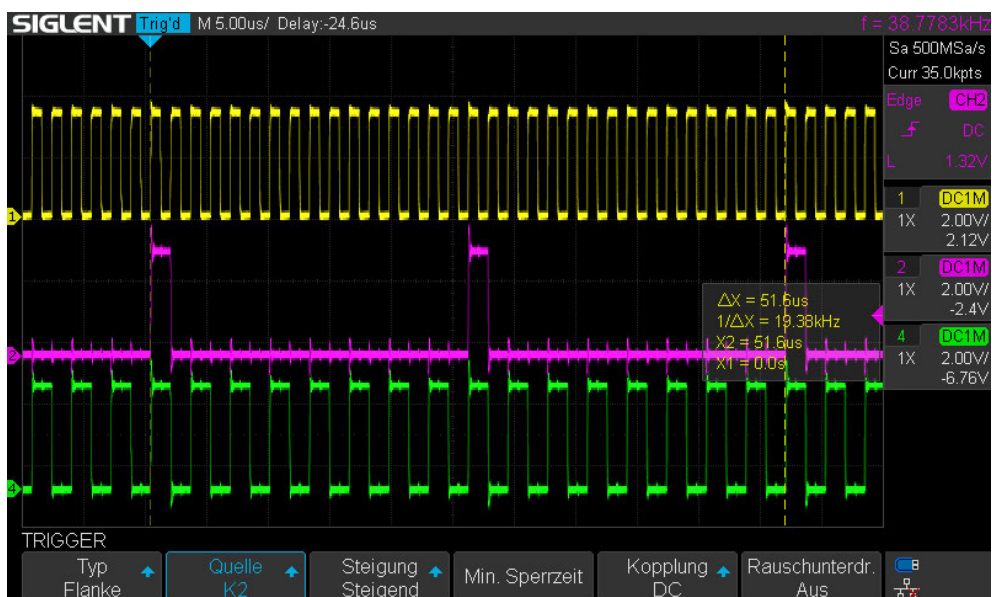


Figure 7.4.: Oscilloscope picture of a double word of PCM3003 signals created by the PLL



Figure 7.4 shows the bit clock signal (yellow  $2\text{ V/div}$ ), the SSInFSS signal (pink  $2\text{ V/div}$ ) and an example data signal (green  $2\text{ V/div}$ ) created by the PLL concept described in Chapter 4.2.2.1.

### 7.3.2. Quartz

This section shows the oscilloscope graphs produced by the quartz concept circuit described in chapter 4.2.2.2.

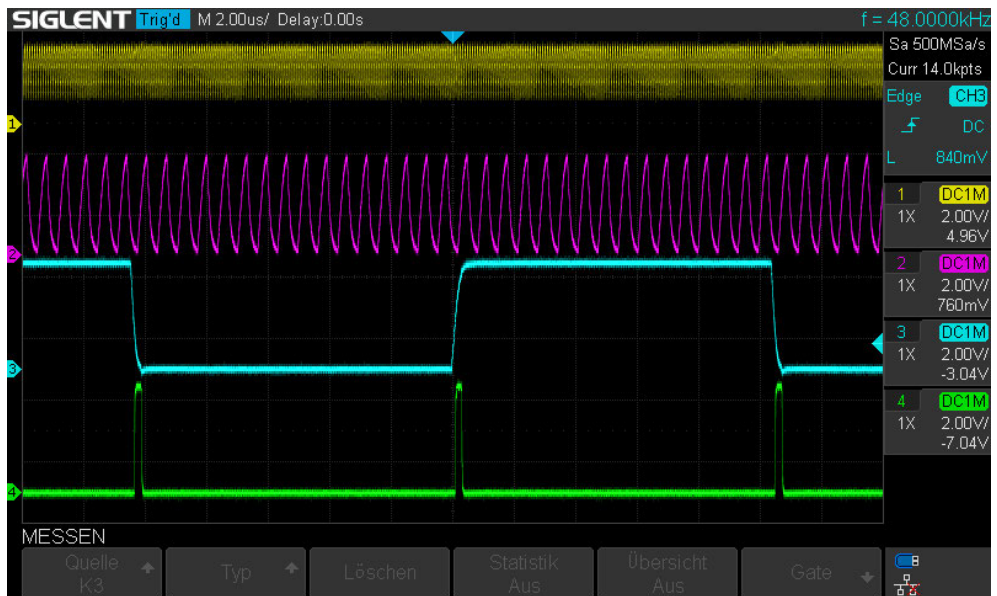


Figure 7.5.: Oscilloscope picture of a double word of PCM3003 signals created by the Quartz concept

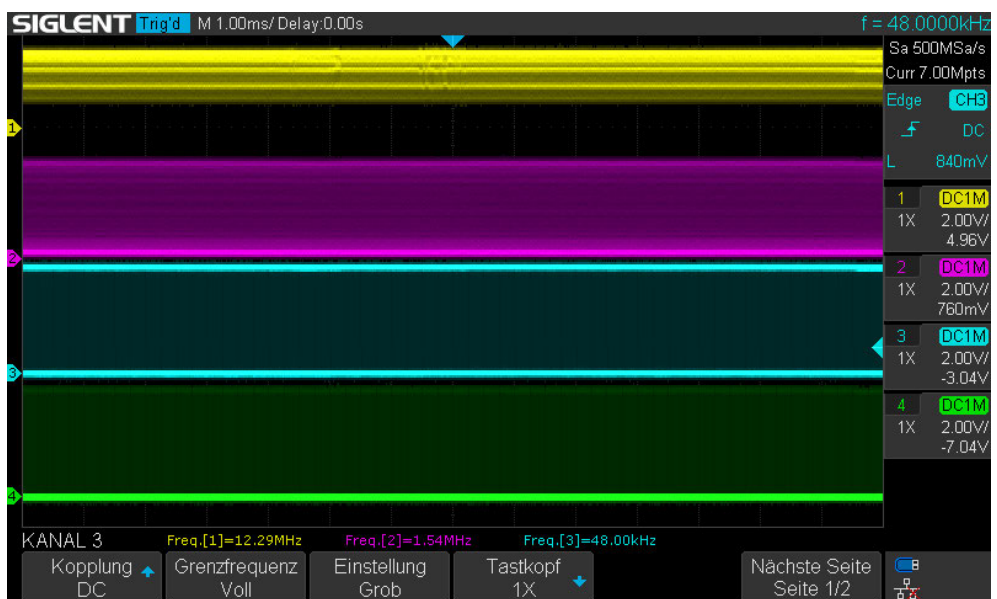


Figure 7.6.: Oscilloscope picture to measure the frequency of the PCM3003 signals created by the Quartz concept

Shown in Figure 7.5 and Figure 7.6 are the precisely by the quartz concept generated PCM3003 signals with a high frequency stability. Shown in yellow is the graph of a the System clock with it's desired frequency of  $12.288\text{ MHz}$  [25]. The green graph shows the Bit clock with it's desired frequency of  $32\text{Bit} \cdot 48\text{ kHz} = 1.536\text{ MHz}$ . Plotted in blue is the word clock with it's desired frequency of  $48\text{ kHz}$  [25]. The green signal shows the SSInFSS signal generated by the logic described in Chapter 4.2.2.2.

## 7.4. MAX232

This part of the chapter shows the oscilloscope graph of a running MAX232 in Figure 7.7.

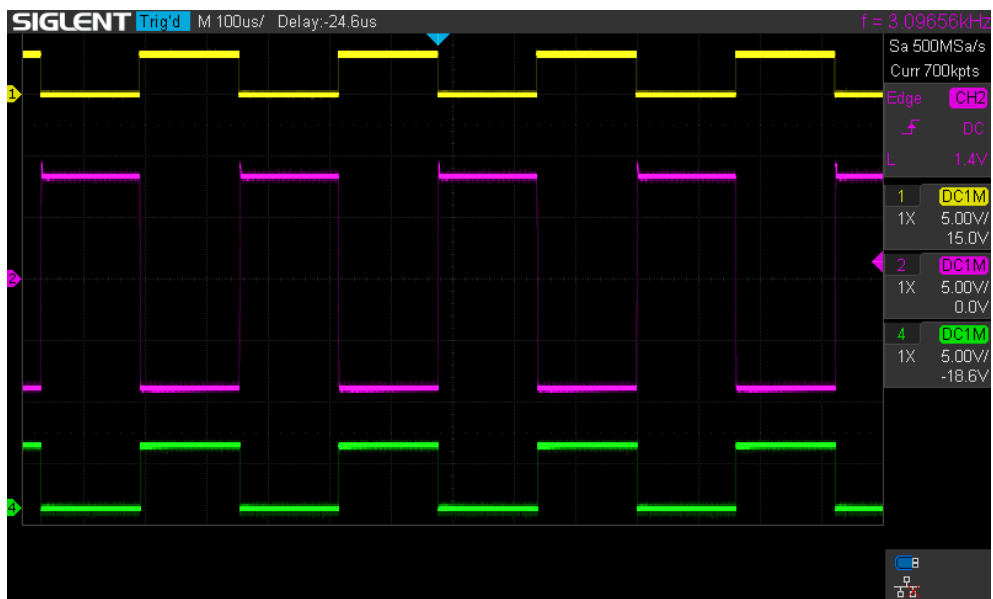


Figure 7.7.: Oscilloscope picture of example MAX232 signals

The Figure 7.7 shows the input signal (yellow colored signal  $5\text{ V/div}$ ) which is produced by the function generator. A pink graph shows the desired signal voltages of  $\pm 8\text{ V}$  ( $5\text{ V/div}$ ) [26] at the output of the MAX232. By connecting the output signal of the MAX232 back to a RS232 input of the MAX232 the green graph ( $5\text{ V/div}$ ) is produced on the oscilloscope at the UART output of the MAX232.

## 7.5. 74LVC125

The following Figure 7.8 shows the oscilloscope graph of 3.3 V a input signal to the 74LVC125 created by the function generator (yellow colored signal 1 V/div) and the matching output signal (pink colored signal 2 V/div)

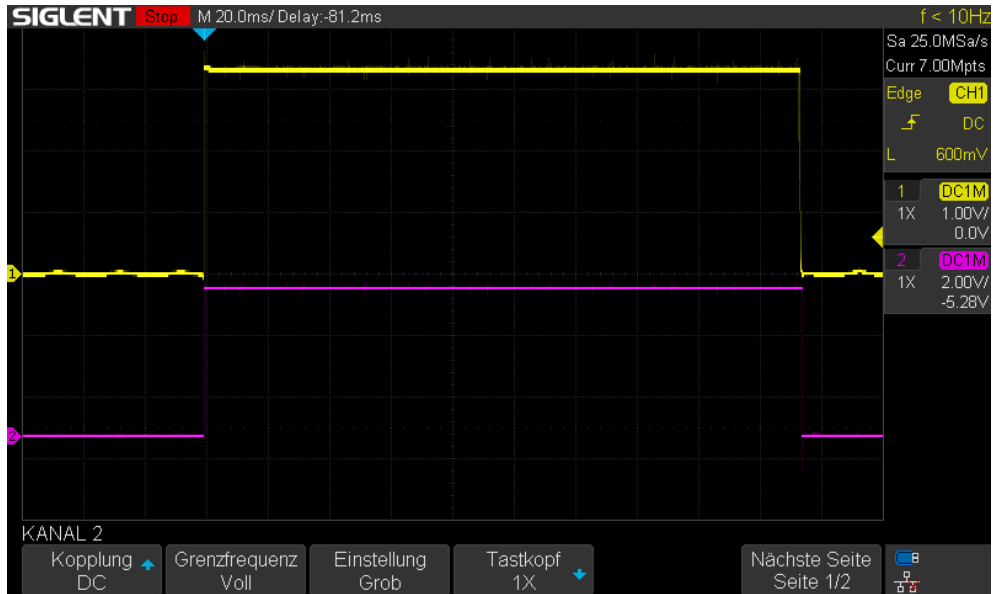


Figure 7.8.: Oscilloscope picture of example 74LVC125 signals

As seen in Figure 7.8 the output voltage has the desired signal voltage of 5 V,

## 8. Assembling of the MSA Board

After the ordered parts and the produced boards are ordered and delivered, the MSA Board can be assembled. The SMD devices on top of the MSA board are soldered by a reflow furnace. To do so the soldering pads of the SMD parts are covered with a soldering paste [66] using the stencil which is delivered with the board. After covering the solder pads with the solder paste and placing the parts on top of it, the board is soldered in the reflow furnace. The reflow furnace, has to be configured with the used soldering pastes temperature graph [66]. After that the other parts are assembled by soldering with a soldering iron.

## 9. Conclusion

The purpose of this thesis was to concept and develop the interface board of an EGD. This interface board is called MSA Board and contains several signal converters, an audio codec, a logic circuit to run the codec, a microphone amplifier and an amplifier for a speaker out put.

As you can see this Thesis is missing a chapter about the final tests of the MSA Board. This chapter is missing because of some problems that have occurred while working on this thesis. Beginning with a software to test all the function the Board should have. This software is not working at the moment. The time I have used to get the PLL concept to run was mach to long and so I had a lack of time at the end of the three month given to do this thesis. The next problem occurred while soldering the components on the MSA Board. Some solder joints where not soldered well in the furnace. This could be a result of using an soldering paste the furnace wasn't used for before and was not optimized to it. Another factor for this is that I had to clean some bridges built with soldering paste between different pads. The cleaning process may have reduced the remaining soldering paste to that extend that the soldering joint could not be made correctly and another possible reason for this can be the polygons used to distribute the supply voltages to the systems of the MSA Board. These polygons act as heat sinks and prohibit the soldering process by cooling down the soldering pads. Because of this reasons I had to fix some soldering joints with a soldering iron and accidentally constructed a soldering bridge while doing that. I could not remove the soldering bridge with the soldering iron. So I have to try it again with flux and a hot air soldering station. The last problem occurred while writing this thesis. In Figure 7.7 the test of the MAX232 is shown. Until now I have accidentally forgotten the fact that the UART signal coming from the MAX232 has a signal voltage of 5 V what is too high of a voltage for the TM4C1294 [11].

The fact that I spent too much time with the PLL concept has an advantage too because while doing this I have learned very much about different IC classes, how to build a a second order RC low pass, how to configure a PLL and how a bad realization of a circuit can interfere with its environment. The microphone circuit and its amplifier are working very well. Likewise the speaker amplifier with its complementary final stage is working better then expected even if the output power may be a little bid low, it should be enough for this purpose. The board layout is very complicated and I have learned a lot about using EAGLE and how to design a board layout. A big help for doing this was the board layout of the EK-TM4C1294XL available at the Texas Instruments website. While studying it for the position of its connectors I noticed that the wires on one side are all vertical and horizontal an the other side. This technique is a huge help to menage space problems. Another big help to menage these problems is to build large supply polygons in own layers. These polygons are good for EMV reasons too. While assembling all the components I have learned much about soldering techniques and the advantages and disadvantages of them. The problem mentioned earlier in this chapter about the high UART output voltage of the MAX232 can maybe fixed by putting two diodes in serial connection with the protection resistor on the TM4C1294 pin. To make

this concept work the internal pull down registers of the Tm4C1294 have to be used [11]. Another concept to fix this problem could be using a TLV431. Both of these concept doesn't look good on the Board bud they could solve the problem.

The final statement of mine to end this Thesis: I liked this thesis a lot because it fits my personal interests, I could use a lot of the stuff I have learned in the previous years on this Thesis and I have learned even more.

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## A. MATLAB Script to calculate the Power dissipation on Transistors

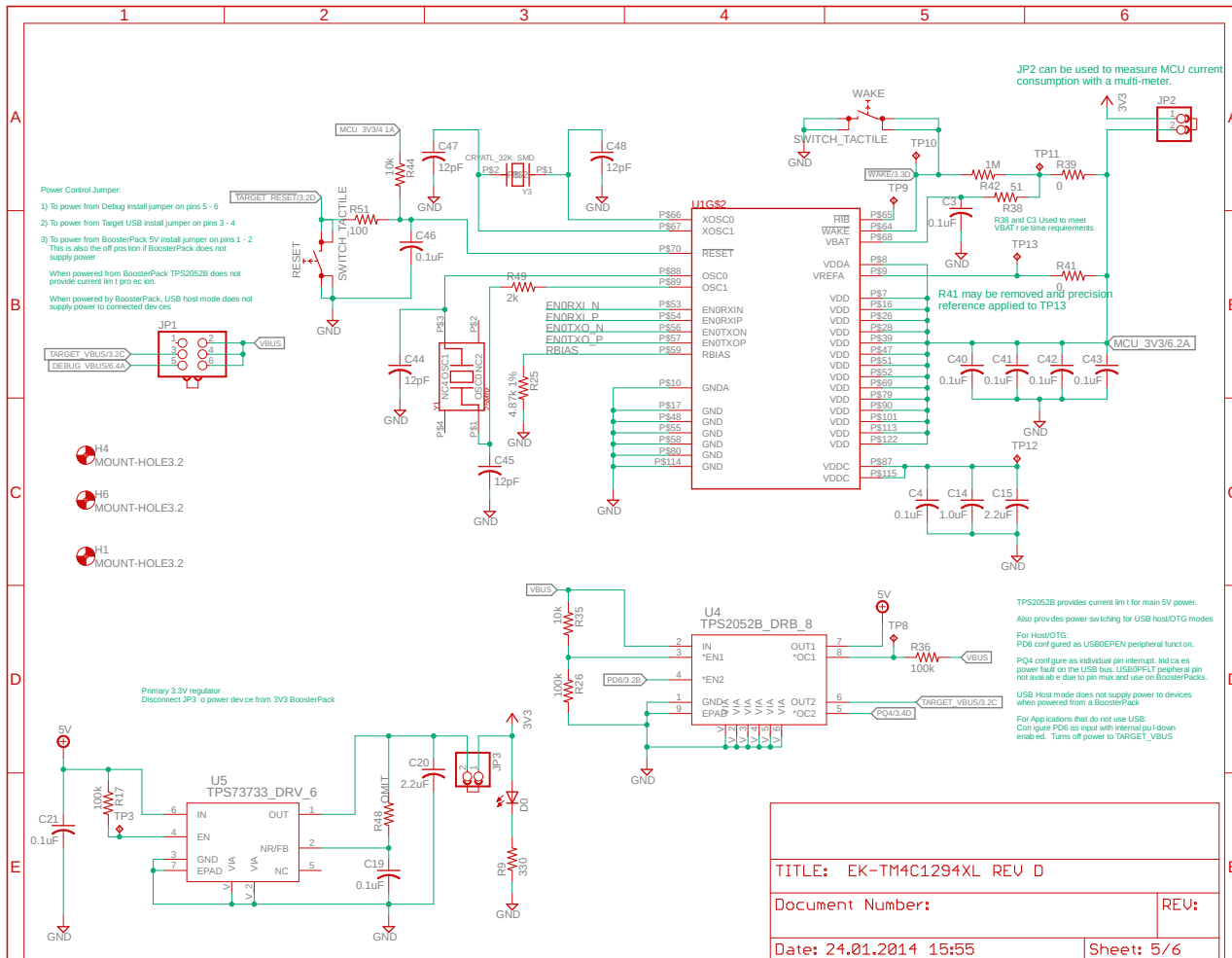
```

1 clear all
2
3 U = 5; % Supply voltage
4 Ubemin = 1.4; % Series of two bipolartransistors
basis emitter voltage
5 Znominal = 4; % Nominal impedance of the speaker
6 Imax = (U - Ubemin)/Znominal; % Maximal current through the
transistors
7 Imin = 0.09; % Minimum current through the
transistors
8 i = Imin:0.001:Imax; % Define current vector
9 u = U:-((U-Ubemin)/(size(i,2)-1)):Ubemin; % Define voltage vector
10 for x = 1:(size(i,2)) % Set loop to calculate a power
vector
11 p(x) = u(x)*i(x); % Calculate the power dissipation
12 end
13 [P,Xmax] = max(p); % Search for the maximum power
dissipation in the powerd dissipation vector
14 figure(1); % Open figure 1
15 yyaxis left; % Define the left Y axis with the
following code lines
16 plot(i, u); % Plot a Voltage graph into figure
1
17 ylabel('Voltage [V]'); % Label the left Y axis
18 hold on; % Save the plot in figure 1
19 yyaxis right; % Define the right Y axis in the
following code lines
20 plot(i,p); % Plot power dissipation graph into
figure 1
21 ylabel('Power dissipation [W]') % Label right Y Axis
22 hold on; % Save power dissipation graph in
figure 1
23 plot(i(Xmax),p(Xmax),'c*'); % Plot a mark at the maximum
powerdissipation
24 title('Power dissipation at the Power amplifier'); % Title figure 1
25 xlabel('Current [A]'); % Label the X axis
26 Text = sprintf('Maximum Power dissipation = %f W',p(Xmax)); % Define a string
27 lgd = legend({'Voltage on Transistors', 'Power dissipation', Text}, 'location',
'southwest'); % Define and set a describing legend
28 title(lgd, 'Legend'); % Title the legend

```

## B. EK-TM4C Powersupply Circuit Diagramm

## B. EK-TM4C Powersupply Circuit Diagramm



## C. Amplifier Circuit Source

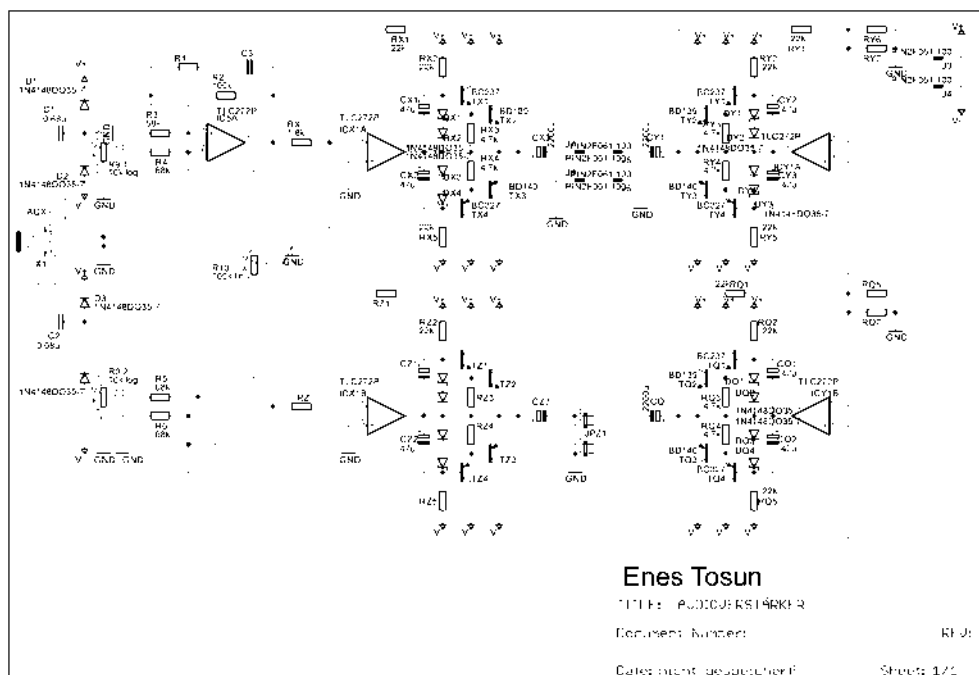


Figure C.1.: Circuit diagram: Original circuit of the speaker amplifier [1]

## D. MATLAB Script to calculate the Signal Amplitude after Filters



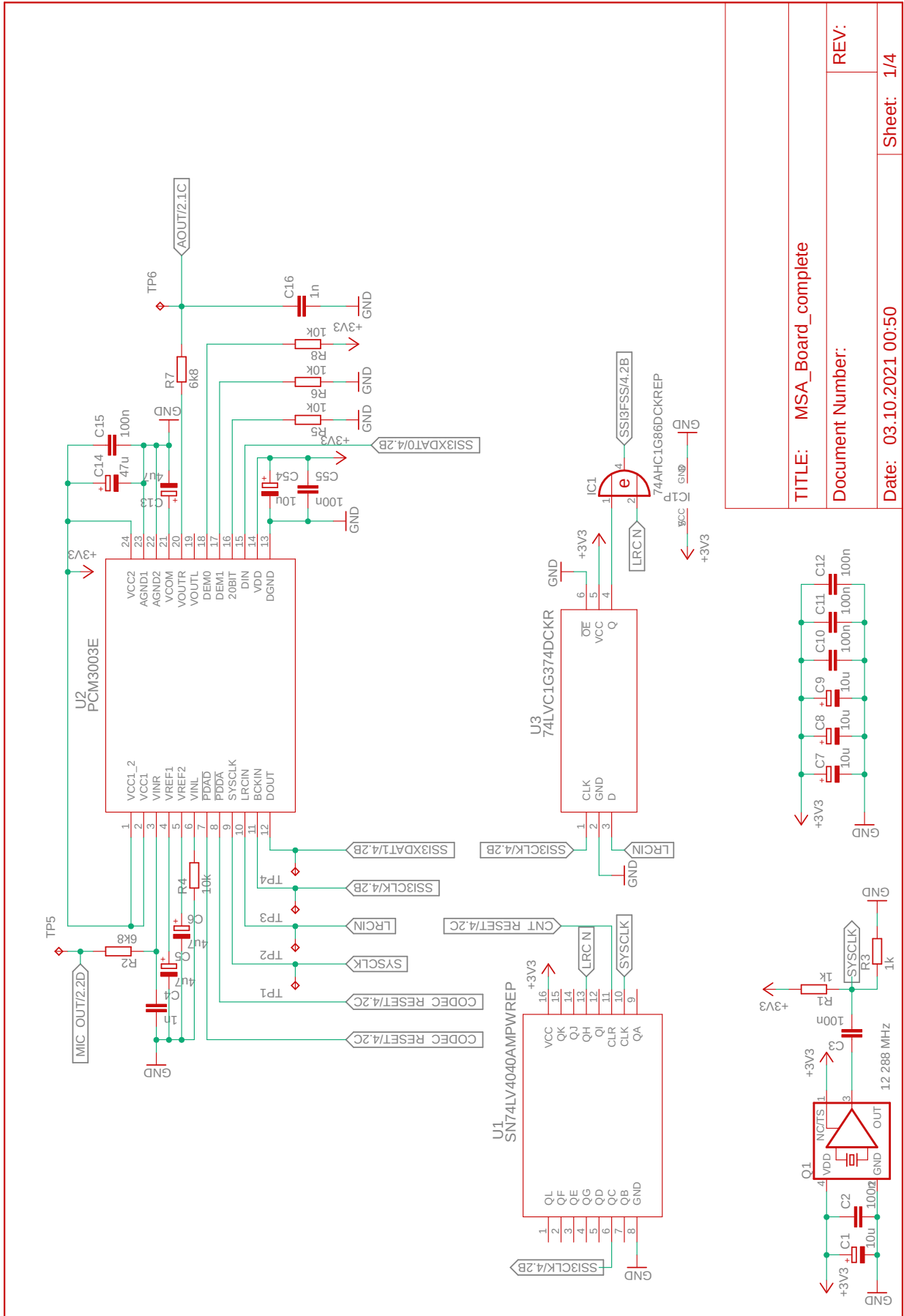
```

1 clear all
2
3 Ub = 3.3; % Supply voltage
4 dynamic_Range = 0.6 * Ub; % Calculate the dynamic range
of the audio codec
5 Uampli_in = dynamic_Range / 2; % Calculate the maximum
amplitude of the audio codec
6 f = 16:1:20000; % Define frequency vector
7 Z1 = 6800; % Define Z1
8 Z4 = 10000; % Define Z4
9 Clp = 1 * 10^(-9); % Define low pass capacity
10 Chp = 3.3 * 10^(-6); % Define high pass capacity
11
12 for x = 1:(size(f,2)) % Set loop to calculate a
vector of putput amlitudes
13     Z2 = 1/(2 * pi * f(x) * Clp); % Calculate Z2 for each
frequency
14     Z3 = 1/(2 * pi * f(x) * Chp); % Calculate Z3 for each
frequency
15     Z2Z3Z4ges = 1/((1/Z2) + (1/(Z3+Z4))); % Calculate the total impedance
of Z2, Z3 and Z4
16     Zges = Z1 + Z2Z3Z4ges; % Calculate the total impedance
of Z1, Z2, Z3 and Z4
17     Uampli_out(x) = Uampli_in * (Z2Z3Z4ges / Zges) * (Z4 / (Z4 + Z3)); % Calculate
the output amplitudes of the filters
18 end
19 [U,Xmax] = max(Uampli_out); % Search for the maximum output
amplitude of the filters
20
21 figure(1); % Set figure 1
22 semilogx(f, Uampli_out); % Plot the amplitude graph on a
semi logarithm sheet
23 ylabel('Voltage [V]'); % Label the Y axis
24 hold on; % Save the plot in figure 1
25 semilogx(f(Xmax),Uampli_out(Xmax),'*'); % Plot a mark on the maximum
amplitude in figure 1
26 title('Affect of the filters on the amplitude of the audio codec'); % title figure
1
27 xlabel('Frequency [Hz]'); % Label X axis
28 Text = sprintf('Maximum anplitude after the filters %f V at %i Hz',Uampli_out
(Xmax), f(Xmax)); % Define output text with maximum output amplitude
29 lgd = legend({'Voltage on Transistors', Text}, 'location', 'southwest'); %
Define legend
30 title(lgd, 'Legend'); % Title legend
31

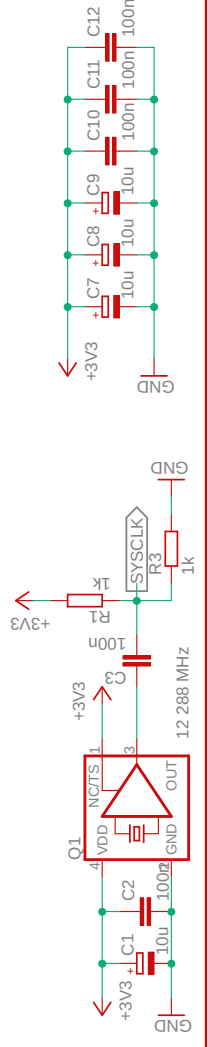
```

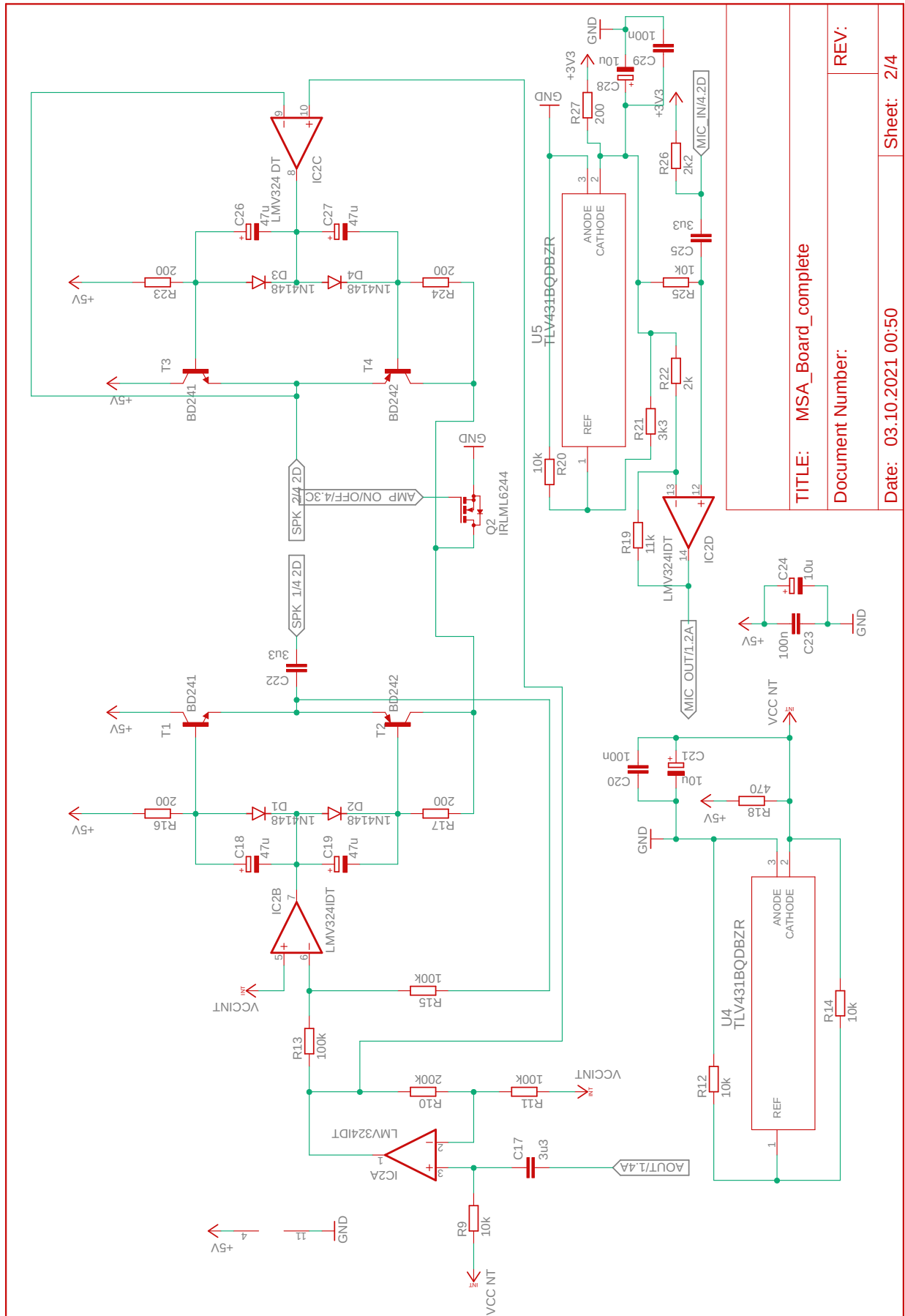
## E. Circuit Diagrams

E. Circuit Diagrams



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Document Number:	REV:
Date: 03.10.2021 00:50	Sheet: 1/4





TITLE: MSA\_Board\_complete

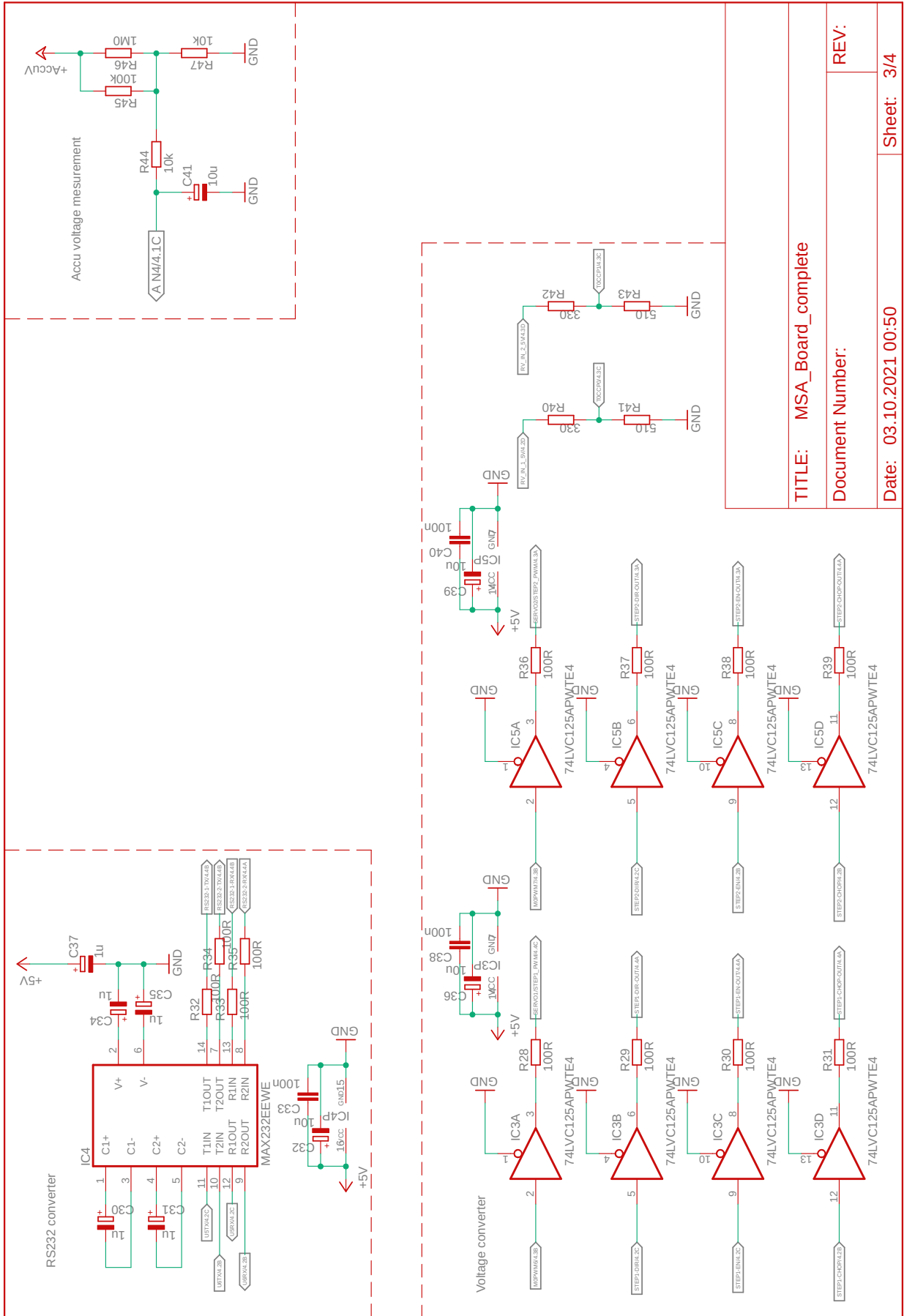
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REV:

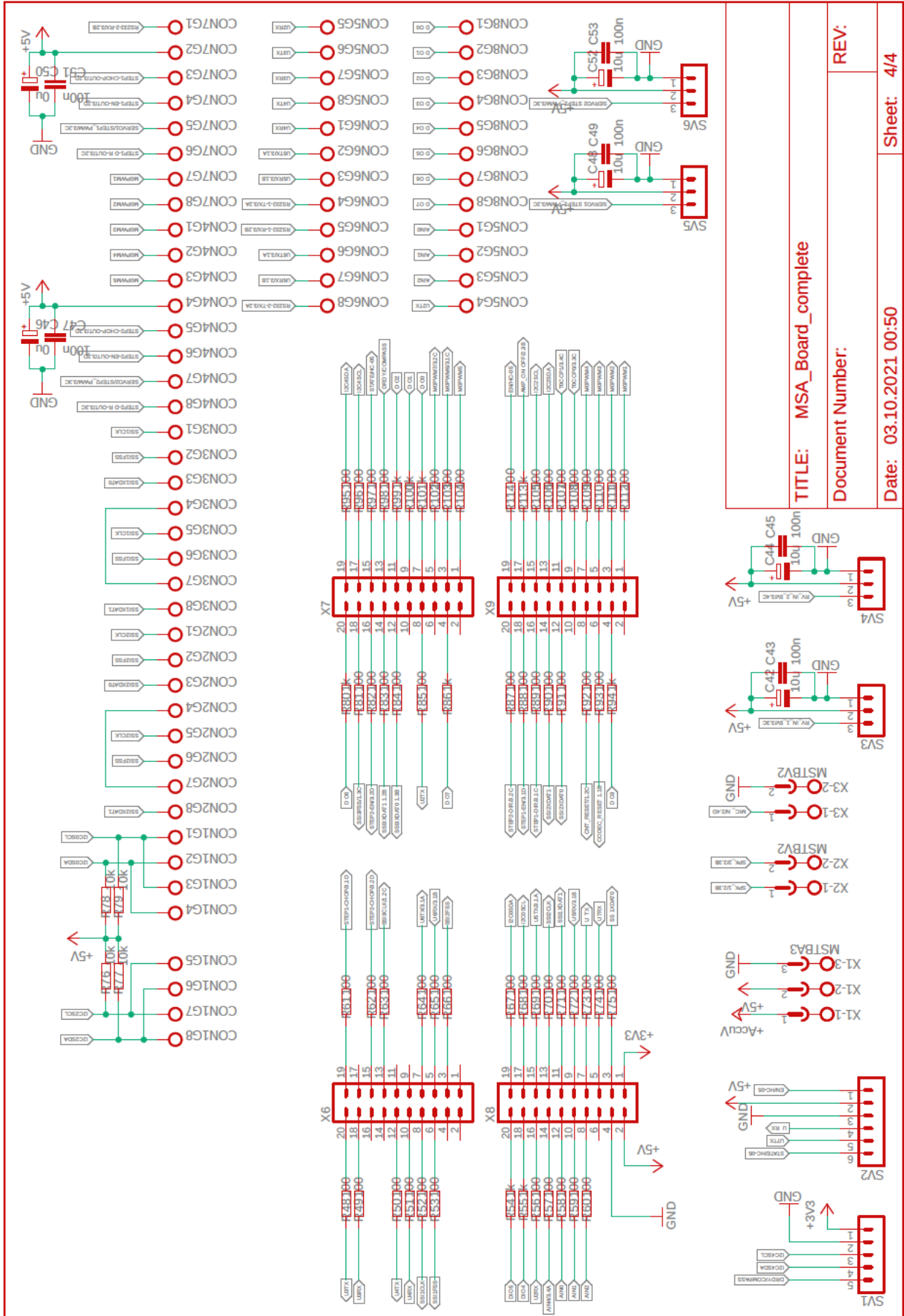
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Sheet: 2/4

E. Circuit Diagrams

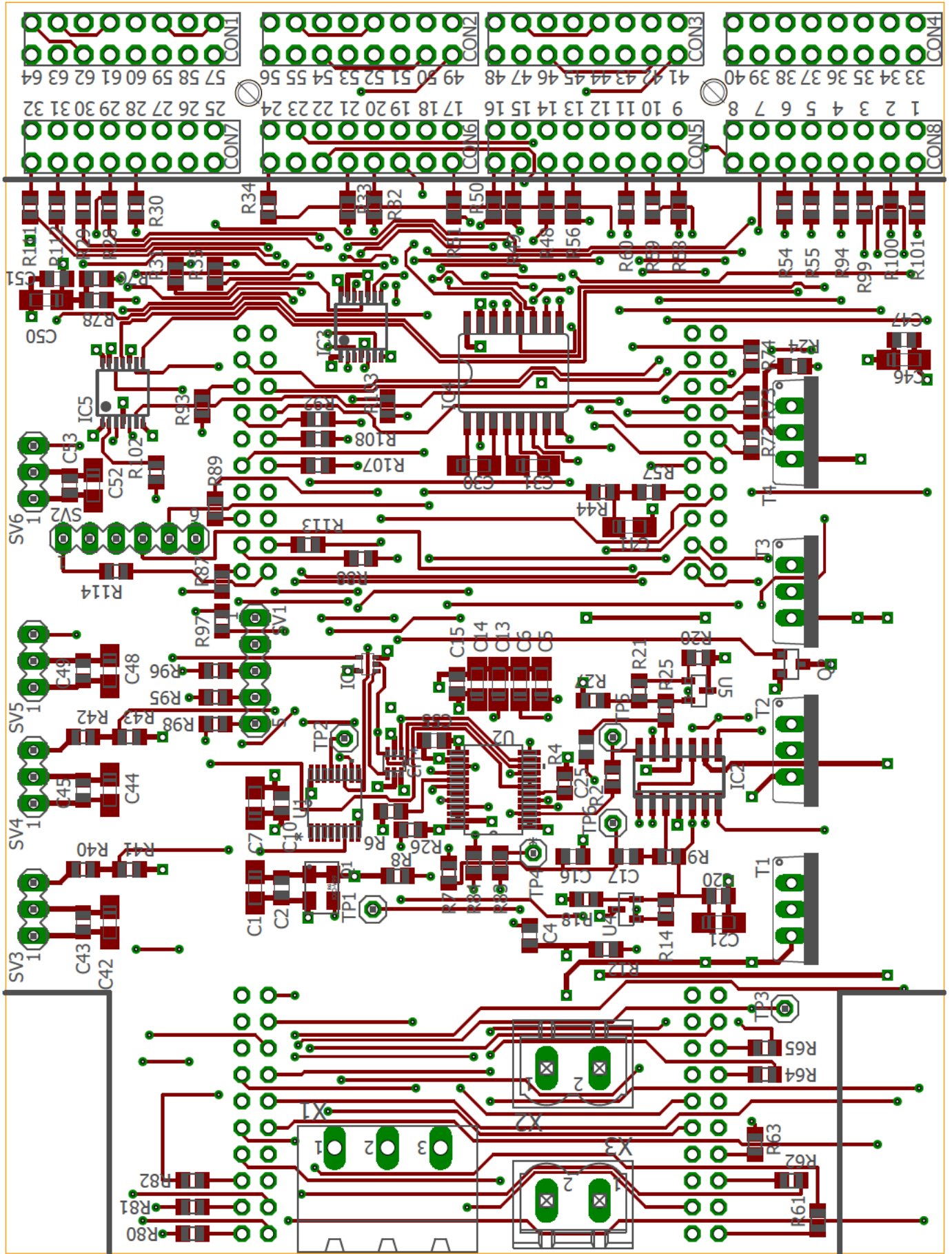


# E. Circuit Diagrams

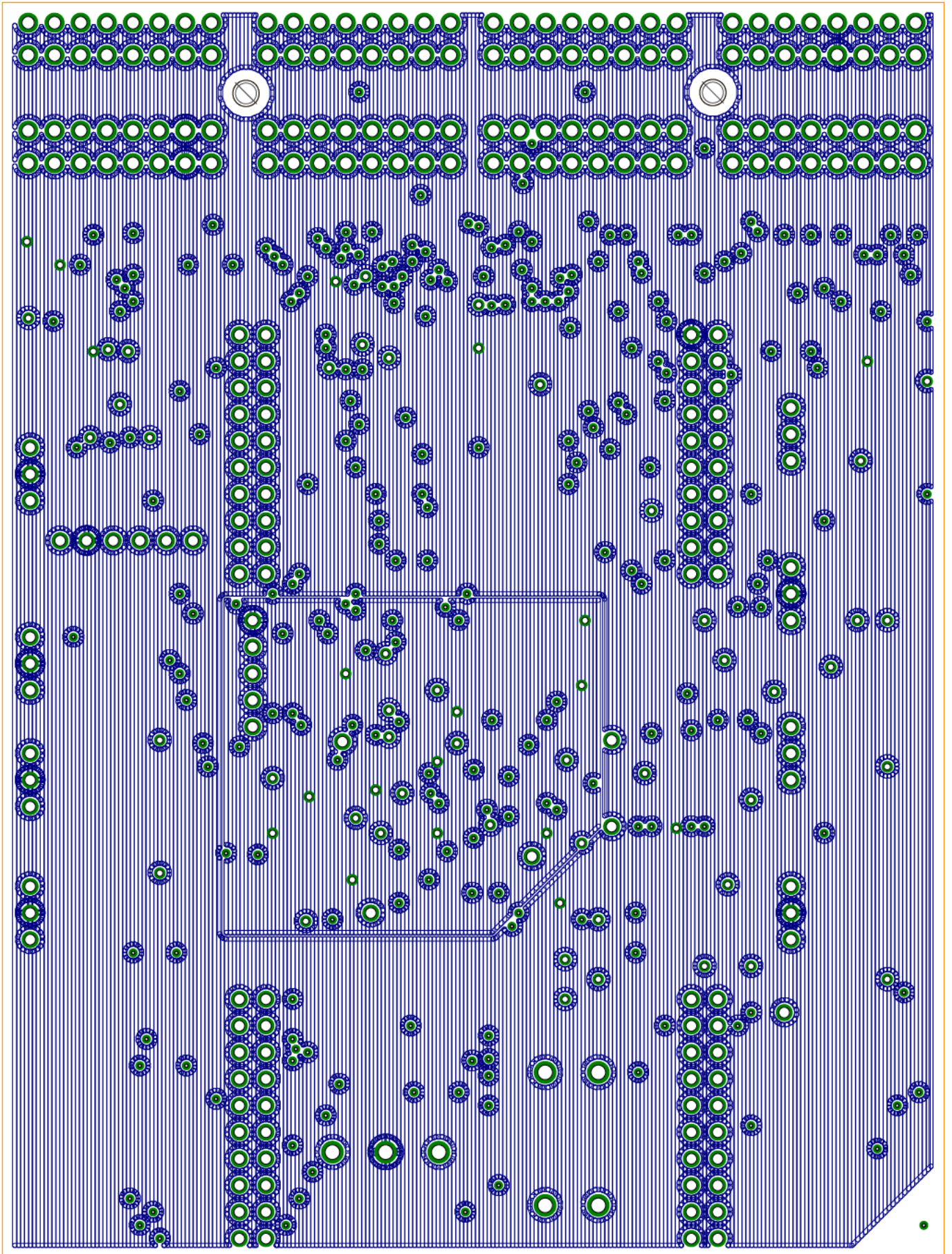


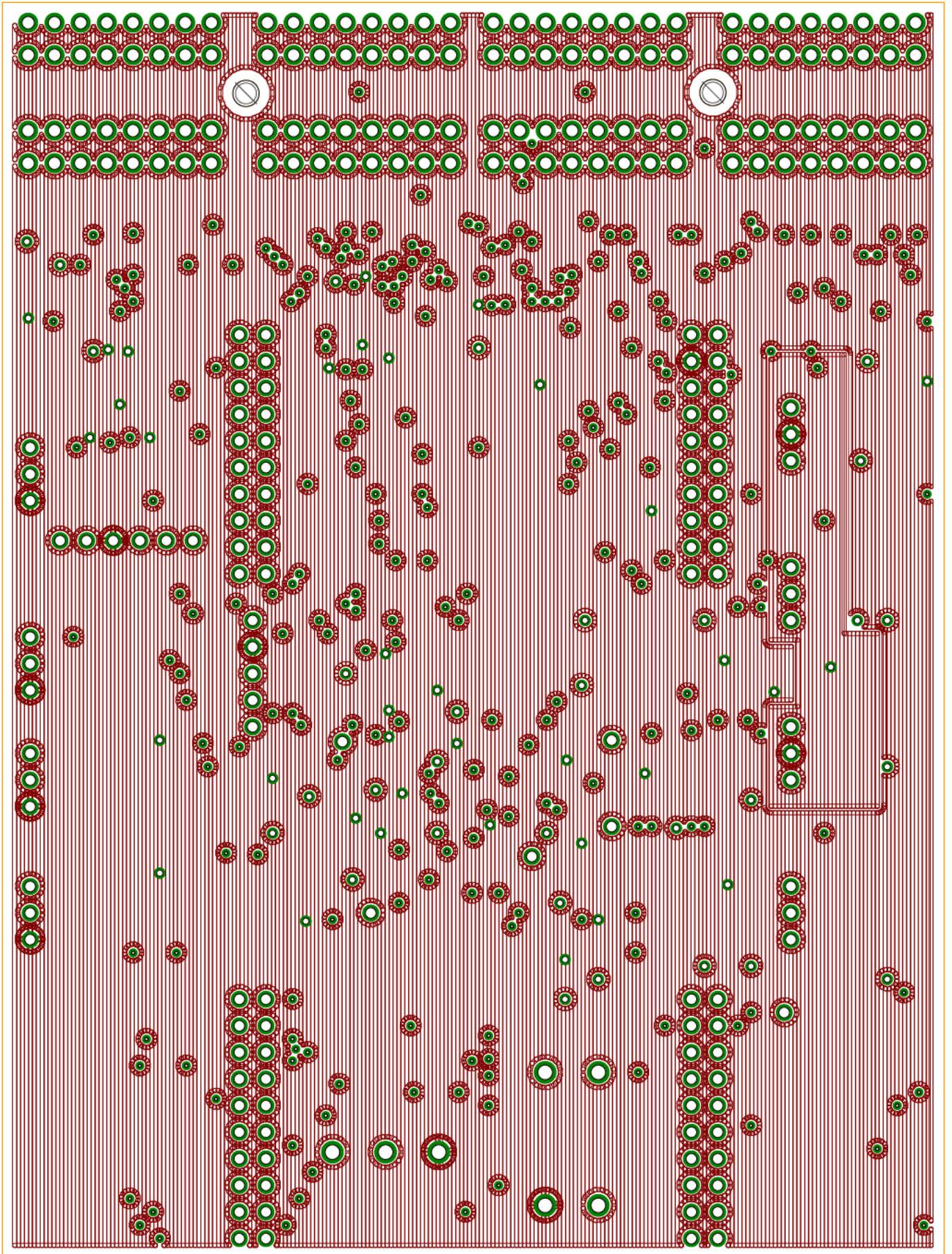
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<b>Date:</b> 03.10.2021 00:50	

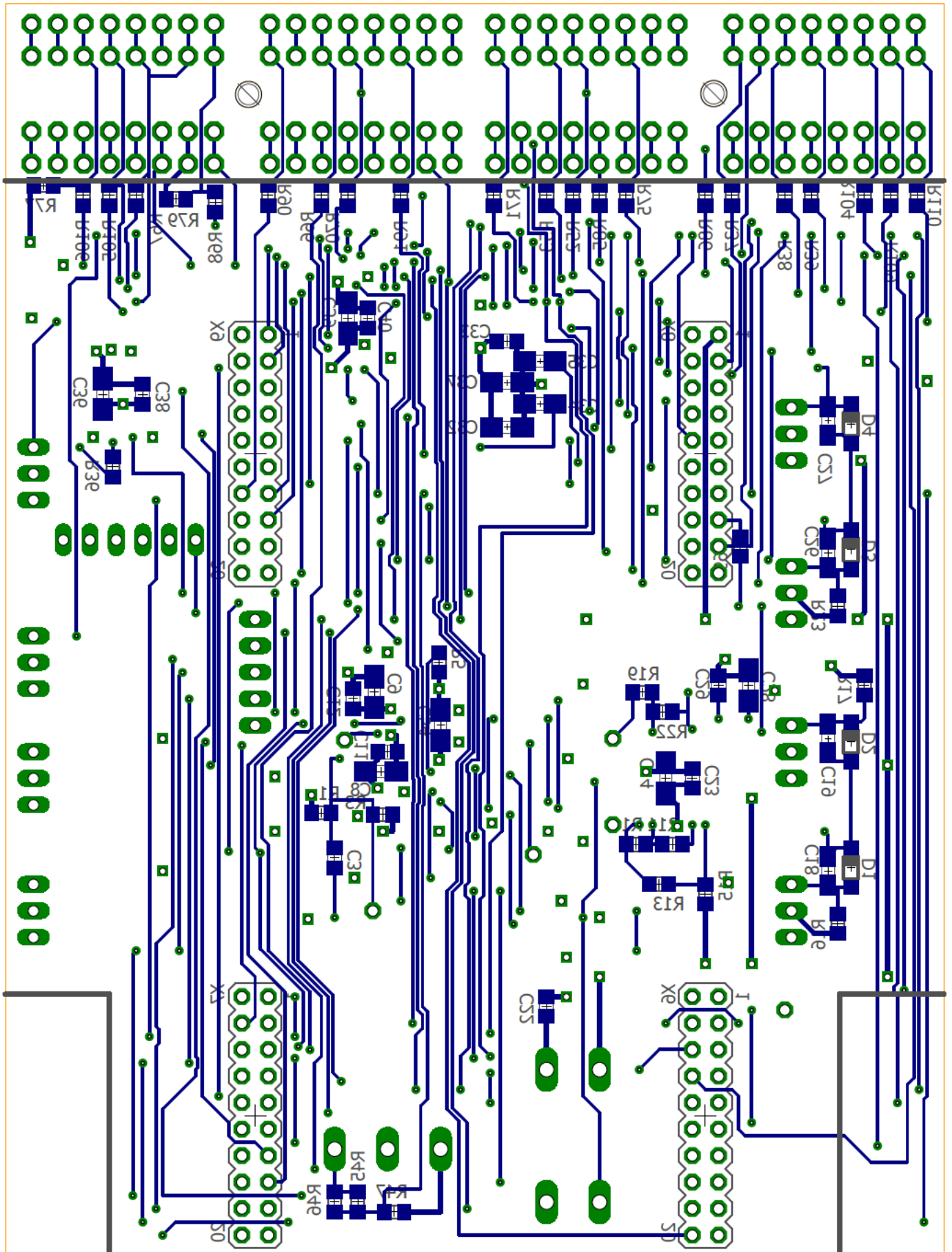
## F. Board Layouts











## G. List of Material

Pos.	Part	Value	Count
1	X6, X7, X8, X9	CONNECTOR	4
2	X1	CONNECTOR	1
3	X2, X3	CONNECTOR	2
4	SV2, TP	CONNECTOR	2
5	SV1	CONNECTOR	1
6	CON1, CON2, CON3, CON4, CON5, CON6, CON7, CON8	CONNECTOR	8
7	SV3, SV4, SV5, SV6	CONNECTOR	4
8	R28, R29, R30, R31, R32, R33, R34, R35, R36, R37, R38, R39, R48, R49, R50, R51, R52, R53, R56, R57, R58, R59, R60, R61, R62, R62, R62, R63, R64, R65, R66, R67, R68, R69, R79, R71, R72, R73, R74, R75, R81, R82, R83, R84, R85, R87, R88, R89, R90, R91, R92, R93, R95, R96, R97, R98, R102, R103, R103, R104, R105, R106, R107, R108, R109, R110, R111, R112, R114	100 Ohm	69
9	R1, R3, R54, R55, R80, R86, R94, R99, R100, R101, R113	1 kOhm	11
10	R4, R5, R6, R8, R9, R12, R14, R20, R25, R44, R47, R76, R77, R78, R79	10 kOhm	15
11	R13, R15, R45	100 kOhm	3
12	R10, R46	1 Mohm	2
13	R19	11 kOhm	1
14	R16, R17, R23, R24, R27	200 Ohm	5
15	R22	2 kOhm	1
16	R26	2,2 kOhm	1
17	R11	270 kOhm	1
18	R40, R42	330 Ohm	2
19	R21	3,3 kOhm	1
20	R18	470 Ohm	1
21	R41, R43	510 Ohm	2
22	R2, R7	6,8 kOhm	2
23	C4, C16	1 nF	2

24	C2, C3, C10, C11, C12, C15, C20, C23, C29, C33, C38, C40, C43, C45, C47, C49, C51, C53, C55	100 nF	19
25	C30, C31, C34, C35, C37	1 $\mu$ F	5
26	C1, C7, C8, C9, C21, C24, C28, C32, C36, C39, C41, C42, C44, C46, C48, C50, C52, C54	10 $\mu$ F	18
27	C17, C22, C25	3,3 $\mu$ F	3
28	C5, C6, C13	4,7 $\mu$ F	3
29	C14, C18, C19, C26, C27	47 $\mu$ F	5
30	D1, D2, D3, D4	1N4148	4
31	U4, U5	TLV431	2
32	T1, T3	BD241	2
33	T2, T4	BD242	2
34	Q2	IRLML6244	1
35	IC2	LMV324	1
36	IC4	MAX232	1
37	IC3, IC5	74LVC125	2
38	Q1	12,288 MHz	1
39	IC1	74LVC1G86	1
40	U1	74LVC4040	1
41	U3	74LVC1G374	1
42	U2	PCM3003	1
43	Heat Sink	18,6 K/W	4
44	Bluetooth modul	HC-05	1

## H. List of Pins used on the EK-TM4C1294XL

H. List of Pins used on the EK-TM4C1294XL

Pos.	MC Pin	IO	Connector	Function	Unit
1	-	-	X8-4	Ground	0
2	-	-	X8-1	+3V3	0
3	-	-	X8-2	+5 V	0
4	29	PH0	X7-13	DRDY/Compass	0
5	30	PH1	X7-15	STATE/HC-05	0
6	84	PL3	X9-19	EN/HC-05	0
7	31	PH2	X9-6	Counter Reset	0
8	32	PH3	X9-8	Codec Reset	0
9	83	PL2	X9-17	Amp_ON/OFF	0
10	109	PN2	X9-16	STEP1-DIR	0
11	110	PN3	X9-18	STEP1-EN	0
12	111	PN4	X6-19	STEP1-CHOP	0
13	103	PP2	X9-20	STEP2-DIR	0
14	104	PP3	X7-16	STEP2-EN	0
15	105	PP4	X6-15	STEP2-CHOP	0
16	78	PM0	X7-7	DIO0	0
17	77	PM1	X7-9	DIO1	
18	76	PM2	X7-11	DIO2	
19	75	PM3	X9-4	DIO3	
20	74	PM4	X8-18	DIO4	
21	73	PM5	X8-20	DIO5	
22	72	PM6	X7-20	DIO6	
23	71	PM7	X7-4	DIO7	
24	37	PA4	X6-18	U3TX	3
25	38	PA5	X6-20	U3RX	2
26	40	PA6	X-16	U2Rx	
27	41	PA7	X7-8	U2TX	0
28	91	PB2	X8-17	I2C0SCL	
29	92	PB3	X8-19	I2C0SDA	1
30	121	PB4	X6-6	SSI1FSS	
31	120	PB5	X6-8	SSI1CLK	7
32	25	PC4	X8-5	U7RX/HC-05	
33	24	PC5	X8-7	U7TX/HC-05	
34	23	PC6	X8-9	U5RX	5
35	22	PC7	X8-15	U5TX	
36	1	PD0	X9-14	SSI2DAT1	2
37	2	PD1	X9-12	SSI2DAT0	
38	3	PD2	X6-3	SSI2FSS	
39	4	PD3	X8-13	SSI2CLK	
40	128	PD7	X8-14	AIN4	4
41	15	PE0	X8-6	AIN3	3
42	14	PE1	X8-8	AIN2	2
43	13	PE2	X8-10	AIN1	1
44	12	PE3	X8-12	AIN0	0
45	123	PE4	X8-3	SSI1XDAT0	1
46	124	PE5	X8-11	SSI1XDAT1	
47	43	PF1	X9-1	MOPWM1	1
48	44	PF2	X9-3	MOPWM2	2
49	45	PF3	X9-5	MOPWM3	3
50	49	PG0	X9-7	MOPWM4	4
51	50	PG1	X7-1	MOPWM5	5



H. List of Pins used on the EK-TM4C1294XL

52	18	PK0	X6-10	U4RX	4
53	19	PK1	X6-12	U4TX	
54	63	PK4	X7-3	M0PWM6/Servo1/Step1	6
55	62	PK5	X7-5	M0PWM7/Servo2/Step2	7
56	61	PK6	X7-17	I2C4SCL/Compass	4
57	60	PK7	X7-19	I2C4SDA/Compass	
58	81	PL0	X9-13	I2C2SDA	2
59	82	PL1	X9-15	I2C2SCL	
60	85	PL4	X9-9	TOCCP0/Receiver_in_1	0
61	86	PL5	X9-11	TOCCP1/Receiver_in_2	0
62	118	PP0	X6-5	U6RX	6
63	119	PP1	X6-7	U6TX	
64	5	PQ0	X6-13	SSI3CLK/Codec	3
65	6	PQ1	X7-18	SSI3FSS/Codec	
66	11	PQ2	X7-12	SSI3XDAT0/Codec	
67	27	PQ3	X7-14	SSI3XDAT1/Codec	

I2C	Uart
Analog In	SPI/SSI
PWM Out	PWM In
	Digital I/O

# I. List of Pins on the main Connectors

I. List of Pins on the main Connectors

Pos.	Connector	Pin	Function	MC PIN	PIN ON MAIN CONNECTORS
1	X1	1	Accu Voltage	-	-
2		2	5 V	-	-
3		3	GND	-	-
4	X2	1	OUT 1	-	-
5		2	OUT 2	-	-
6	X3	1	MIC IN	-	-
7		2	GND	-	-
8	SV1	1	3,3 V	-	-
9		2	GND	-	-
10		3	I2C_4_SCL	PK6	-
11		4	I2C_4_SDA	PK7	-
12		5	DRDY/COMPASS	PH0	-
13	SV2	1	5 V	-	-
14		2	GND	-	-
15		3	U7TX	PC5	-
16		4	U7RX	PC4	-
17		5	KEY/HC-05	PH1	-
18		6	NC	-	-
19	SV3	1	GND	-	-
20		2	5 V	-	-
21		3	TOCCP0/Receiver_in_1	PL4	-
22	SV4	1	GND	-	-
23		2	5 V	-	-
24		3	TOCCP1/Receiver_in_2	PL5	-
25	SV5	1	GND	-	-
26		2	5 V	-	-
27		3	SERVO1_PWM/MOPWM6	PK4	-
28	SV6	1	GND	-	-
29		2	5 V	-	-
30		3	SERVO2_PWM/MOPWM7	PK5	-
31	CON_1	1	I2C0SCL	PB2	57
32		2	I2C0SDA	PB3	58
33		3	I2C0SCL	PB2	59
34		4	I2C0SDA	PB3	60
35		5	I2C2SCL	PL1	61
36		6	I2C2SDA	PL0	62
37		7	I2C2SCL	PL1	63
38		8	I2C2SDA	PL0	64
39	CON_2	1	SSI2CLK	PD3	49
40		2	SSI2FSS	PD2	50
41		3	SSI2XDAT0/SPI2_SLAVE1_MOSI	PD1	51
42		4	CASCADE_SPI2_SLAVE1_MISO	-	52
43		5	SSI2CLK	PD3	53
44		6	SSI2FSS	PD2	54
45		7	CASCADE_SPI2_SLAVE2_MOSI	-	55
46		8	SSI2XDAT1/SPI2_SLAVE2_MISO	PD0	56
47	CON_3	1	SSI1CLK	PB5	41
48		2	SSI1FSS	PB4	42
49		3	SSI1XDAT0/SPI1_SLAVE1_MOSI	PE4	43
50		4	CASCADE_SPI1_SLAVE1_MISO	-	44
51		5	SSI1CLK	PB5	45

I. List of Pins on the main Connectors

52		6 SSI1FSS	PB4	46
53		7 CASCADE_SPI1_SLAVE2_MOSI	-	47
54		8 SSI1XDAT1/SPI1_SLAVE2_MISO	PE5	48
55	CON_4	1 MOPWM3	PF3	33
56		2 MOPWM4	PG0	34
57		3 MOPWM5	PG1	35
58		4 STEP2-COMM	-	36
59		5 STEP2-CHOP-OUT	PP4	37
60		6 STEP2-EN-OUT	PP3	38
61		7 SERVO2/STEP2_PWM	PK5	39
62		8 STEP2-DIR-OUT	PP2	40
63	CON_5	1 AIN0	PE3	9
64		2 AIN1	PE2	10
65		3 AIN2	PE1	11
66		4 U2TX	PA7	12
67		5 U2RX	PA6	13
68		6 U3TX	PA4	14
69		7 U3RX	PA5	15
70		8 U4TX	PK1	16
71	CON_6	1 U4RX	PK0	17
72		2 U5TX	PC7	18
73		3 U5RX	PC6	19
74		4 U5TX/RS232-1-TX	PC7	20
75		5 U5RX/RS232-1-RX	PC6	21
76		6 U6TX	PP1	22
77		7 U6RX	PP0	23
78		8 U6TX/RS232-2-TX	PP1	24
79	CON_7	1 U6RX/RS232-2-RX	PP0	25
80		2 STEP1-COMM/ 5 V	-	26
81		3 STEP1-CHOP-OUT	PN4	27
82		4 STEP1-EN-OUT	PN3	28
83		5 SERVO1/STEP1_PWM	PK4	29
84		6 STEP1-DIR-OUT	PN2	30
85		7 MOPWM1	PF1	31
86		8 MOPWM2	PF2	32
87	CON_8	1 DIO0	PM0	1
88		2 DIO1	PM1	2
89		3 DIO2	PM2	3
90		4 DIO3	PM3	4
91		5 DIO4	PM4	5
92		6 DIO5	PM5	6
93		7 DIO6	PM6	7
94		8 DIO7	PM7	8

## J. Assembled MSA Board

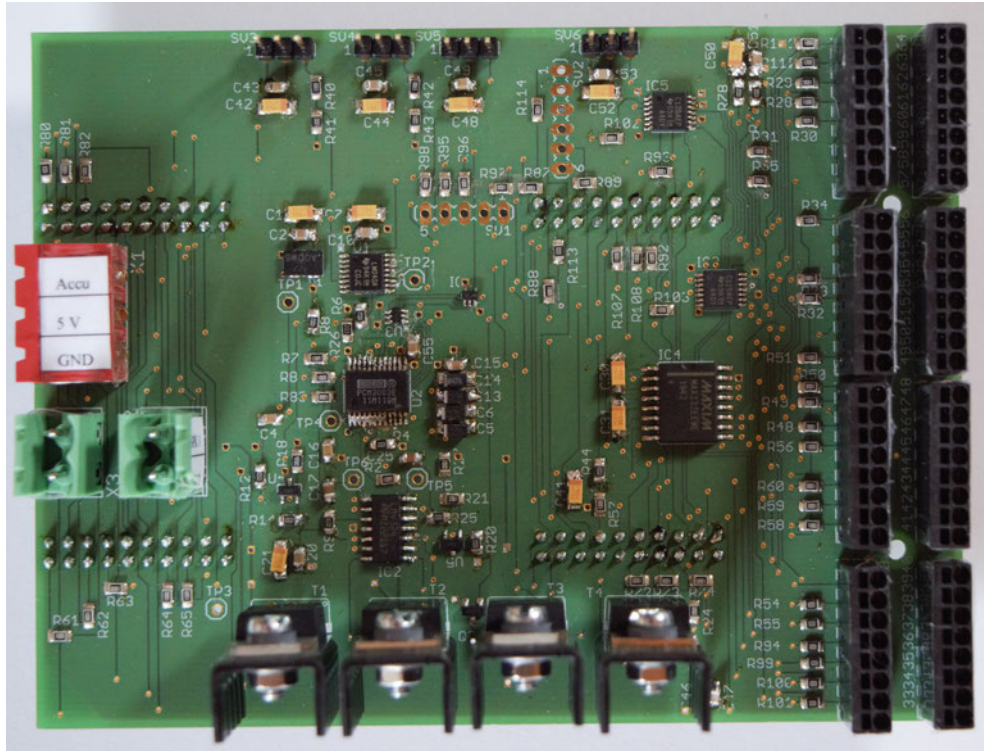


Figure J.1.: Top view on the assembled MSA Board

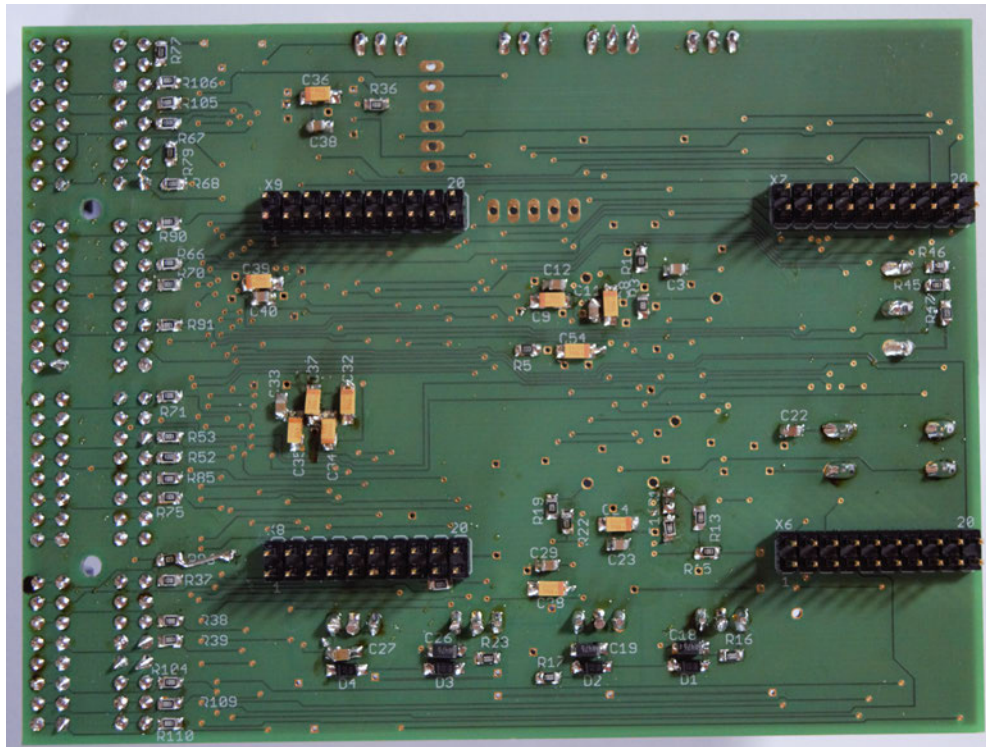


Figure J.2.: Bottom view on the assembled MSA Board

# Declaration

I declare that this Bachelor Thesis has been completed by myself independently without outside help and only the defined sources and study aids were used.

\_\_\_\_\_  
City

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Date

\_\_\_\_\_  
Signature

