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Automated Harness Verification System

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Abstract

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The purpose of this thesis is to design an automated harness verification system. The system will be used by ICEYE's assembly, integration, and testing engineers to verify most types of cables before they are integrated into the satellites. Currently, all verifications are performed manually using an off-the-shelf multimeter.

The modular PCB design consists of two main parts: the main board and the adapter boards. The latter are customized to accommodate testing with most of the connectors used.

An Arduino Due was chosen as a platform to develop the firmware of the printed circuit board. On top of that, python automation is used to support the verification: retrieving harness specs, testing, and finally reporting to the client's internal test data management system.

First, two EVAL-16TSSOPEBZ evaluation boards, two ADG739 4:1 MUX/DEMUX, and an Arduino Uno was used to test the concept and the initial FW of the PCB. Following that, the design was expanded to support up to 100 wire cables.

Unfortunately, the testing of the final PCB could not be carried out due to the time constraints. In addition to the fact that the board had to go through several redesigns. The design of a mechanical supporting structure and a graphical user interface is not part of this project's scope.

Keywords: modularized testing, harness, wire assemblies, automatic test equipment IPC/WHMA A-620 standard.

Contents

List of Abbreviations

ADC: Analog to digital converter

AIT: Assembly, integration, and testing

AVdd: Analog Supply Voltage

DEMUX: Demultiplexer

DVdd: Digital Supply Voltage

FW: Firmware

GUI: Graphical User Interface

IPC: Institute for Interconnecting and Packaging Electronic Circuits

LDO: Low-dropout Linear Regulator

LED: Light Emitting Diode

MUX: Multiplexer

PCB: Printed circuit board

PSU: Power Supply

SAR: Synthetic Aperture Radar

SPI: Serial Peripheral Interface

WHMA: Wiring Harness Manufacturer's Association

1 Introduction

ICEYE is a Finnish new space company with the largest constellation of synthetic aperture radar satellites. With more than 15 satellites in orbit, they can deliver reliable earth observation data no matter the weather condition and time of the day [1]. Figure 1 shows one of ICEYE's latest Satellites right before launch.

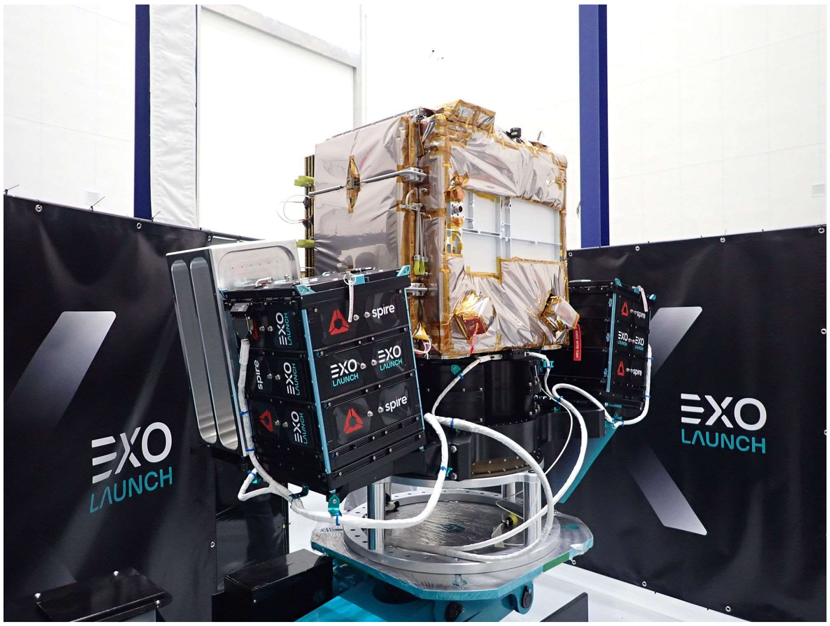

Figure 1: One of ICEYE's satellites ready for launch on the SpaceX Transporter-5 mission.

ICEYE is the client of this project, precisely, its AIT department.

The main purpose of this project was to facilitate the verification process of harnesses before they are integrated into the satellites. In other words, making the process more efficient, less time-consuming, and producing accurate results.

Currently, the verification is completed manually using a multimeter to detect any defect, mostly performing a continuity test. For an application that requires extreme accuracy, this method is not the best choice to opt for, as some faults cannot be detected by a microscope and this type of electrical testing; will remain unnoticed.

Moreover, while using an off-the-shelf multimeter can be manageable for some cables, it gets more and more challenging with larger and more complicated harnesses where test points are over the hundreds. Moreover, there is always the possibility of human error. To avoid that most of the harnesses are verified twice by two different technicians, however, that is not an efficient allocation of resources and time.

The majority of harnesses used are manufactured in-house using a wide range of connectors: GMMD, Micro D sub, Coax, and Harwin to list a few. For this reason, harness testing systems available on the market, such as Cirris, CableEye, and others could not be used, as purchasing only one solution will not cover the entire range of test situations. Figures 2 and 3 present these available solutions.

Figure 2: CIRRIS CR harness tester [2].

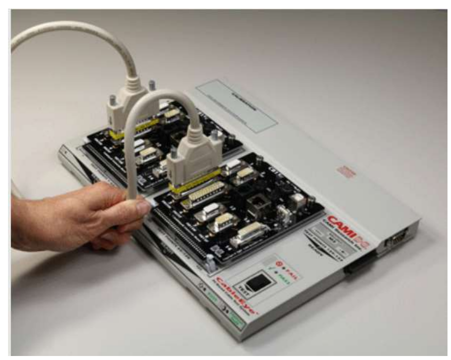

Figure 3: CableEye harness tester [3].

To ensure a long lifetime of the satellites in space, all the subsystems on board must be tested thoroughly taking all possible failures or damages into consideration before launch. The nature of the application makes it quite hard to recover from a failure if discovered in orbit, and sometimes that means the entire system is unfunctional.

Several tests are conducted on each harness. First starting with inspection and mechanical tests then electrical tests. Only the latter is the topic of this thesis. The following section will present industry and user requirements.

2 Project Requirement and Theory

This section will mainly address the project requirements, both from a user and industry point of view. In the second part of the section, an introductory background theory is presented.

2.1 Project Requirements

Principally, the system must detect different defect types that could be encountered and document these results as part of the verification report. These defects could be broken wires, mixed, cross-over, loose connections, or short circuits [6].

The causes of these defects can range from human error, as well as the quality of the materials, tools, and processes used [4; 5]. Examples of fault causes are bad soldering, faulty crimps, or recessed pins [6].

There were two types of requirements to be considered to complete the design of this system. First, industry requirement; more precisely IPC/WHMA-A620 standard [7]: requirement and acceptance of cable and wire and harness assemblies. Second, user-defined requirements.

2.1.1 Industry Requirement

Table 1 lists all the electrical tests required by the IPC/WNHA- A620 Standard [7]. All harness assemblies used in this application are considered a class 3 product and must adhere to the requirement for this class. In this case, a continuity test and short test must be conducted for all assemblies. [7,19-3.]

Continuity test verifies that the point-in-point electrical connections conform to the engineering documentation with minimum requirements of 2 Ω, or 1 Ω plus the maximum resistance which is specified by the wire. [7,19-4.]

Testing for short circuits is a low-voltage test used to detect unintended connections. No minimum requirements have been set for this test. However, a maximum voltage and or current should be specified when components within an assembly may be damaged by this test. [7,19-5.]

2.1.2 User Requirement

Before the kick-off of the project, the client has provided a set of requirements to be met for the end product. These are as follows:

- The PCB should support testing of up to 90-100 wire cables.
- 4-wire Kelvin sensing method should be used to measure cable impedance, using a 10mA sensing current with 1mOhm accuracy.
- A modular design was requested including the main board and swappable adapters boards that could be identified by the software.
- The verification program should be controllable using Python.
- The program should be able to import cable and harness assembly specifications from RapidHarness and export the verification results to WATS and Jira

2.2 Background Theory

The system is based on the 4-wire measurement technique, also named Kelvin sensing. A known current is forced through the wire under test, then the voltage drop developed across it is measured. Fundamentally, we can conclude the impedance of the wire, since it is a ratio of the voltage drop over the current passing through the wire based on Ohm's law [8].

The difference between 2-wire and 4-measurement is in their accuracy. The 2-wire measurement gives quite relative results compared to the absolute accuracy of the 4-wire method, allowing us to measure impedances of less than 0.1 ohms [9,3].

The reason behind this lies in the fact that the impedances of the measurement leads are eliminated by moving them to the endpoints where the leads of the precise current source are connected. Hence the 4-wire measurement term. In other words, the measurement leads in this test setup carry almost no current making the measurement independent from their impedances. [6.]

Figures 4 and 5 illustrate the 2-wire and 4-wire measurement fixtures respectively.

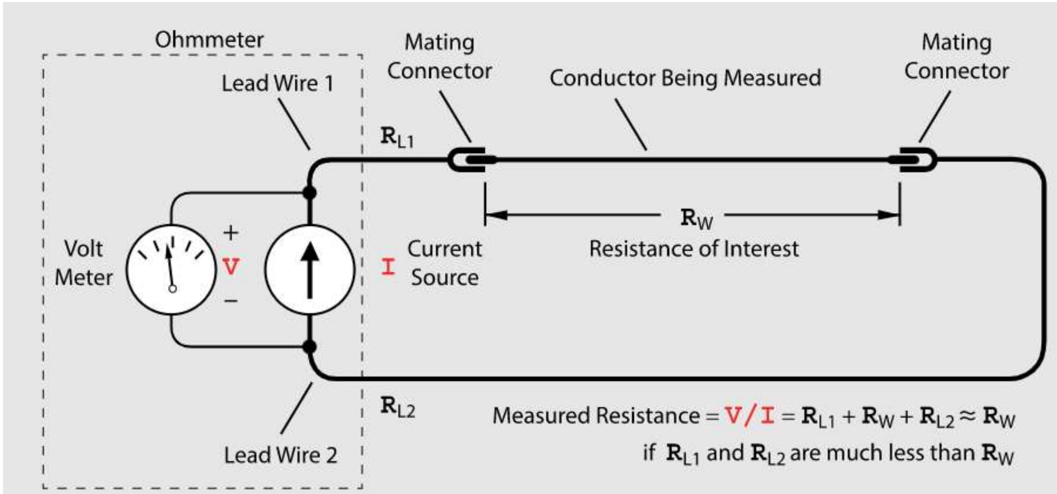

Figure 4: 2-wire measurement fixture [6].

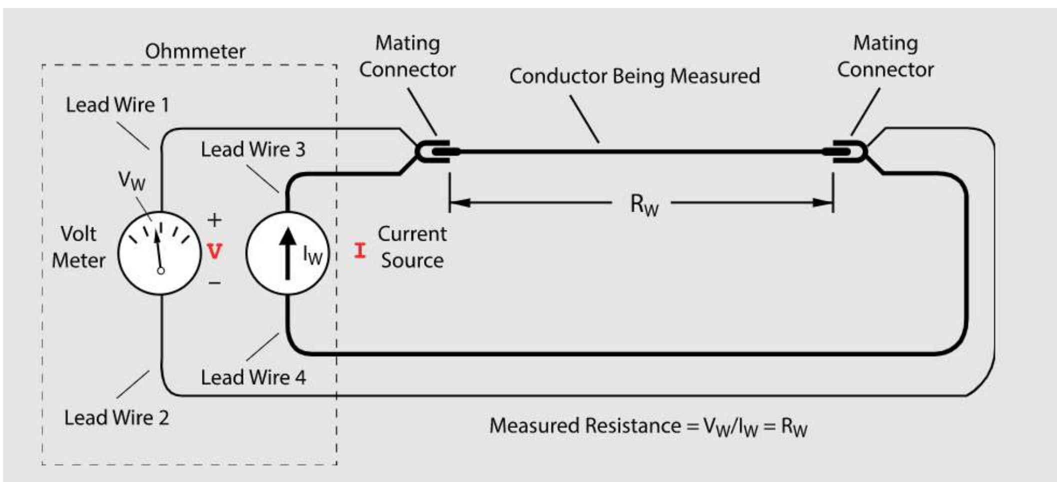

Figure 5: 4- wire measurement fixture [6].

3 Proof of Concept and Component Selection

3.1 Proof of concept

Initially, a small test was conducted as a means of proof of concept. To be able to perform the 4-wire measurement on a 4-pin to 4-pin cable, two EVAL-16TSSOPEBZ evaluation boards (see figure 6) with two ADG739 multiplexers, in addition to an Arduino Uno were used. Here a 34461A keysight precision digital multimeter was used to replace the current source and voltage-sensing circuitry in the setup.
The idea behind the test is to simulate a good, a broken, and a loose connection, and then measure the variation in impedances.

Figure 7 displays a diagram of the test setup. Each wire is assigned 4 pins: a pair for the current source: one pin from MUX 1 side A and a second from MUX 2 side A; and a pair for the voltage sense: one pin from MUX 1 side B and one from MUX 2 side B. The current is pushed through the A sides and the voltage is measured across the B sides. Using the Arduino SPI communication library, a simple script was made to close the associated switches for each wire, the measurement is then performed, results are recorded, then the next four switches for the next connection are closed and the same process is repeated.

Figure 6: EVAL-16TSSOPEBZ board [10].

3.2 Component Selection

Seeing the concept in practice, it was time to select the components to be used on the end product, while expanding the capacity to up to 90-100 wire cables. Also, current source and measurement circuits were to be chosen to meet the user-defined requirements mentioned earlier. A current sense of 10mA and accuracy of 1mohm were to be achieved.

To list the key circuit or components of this design:

- MUX pairs used to provide all the necessary 4-wire measurement connections needed up to 100 pins.
- Precision and reliable current source.
- Instrumentation differential opamp which drives a high-resolution ADC.
- Microprocessor.

Figure 8 shows how the different measurement circuits are interconnected from a top-level schematic sheet. A detailed description of each of these elements can be found in their corresponding sections below.
Moreover, the schematics are available in Appendix 1.

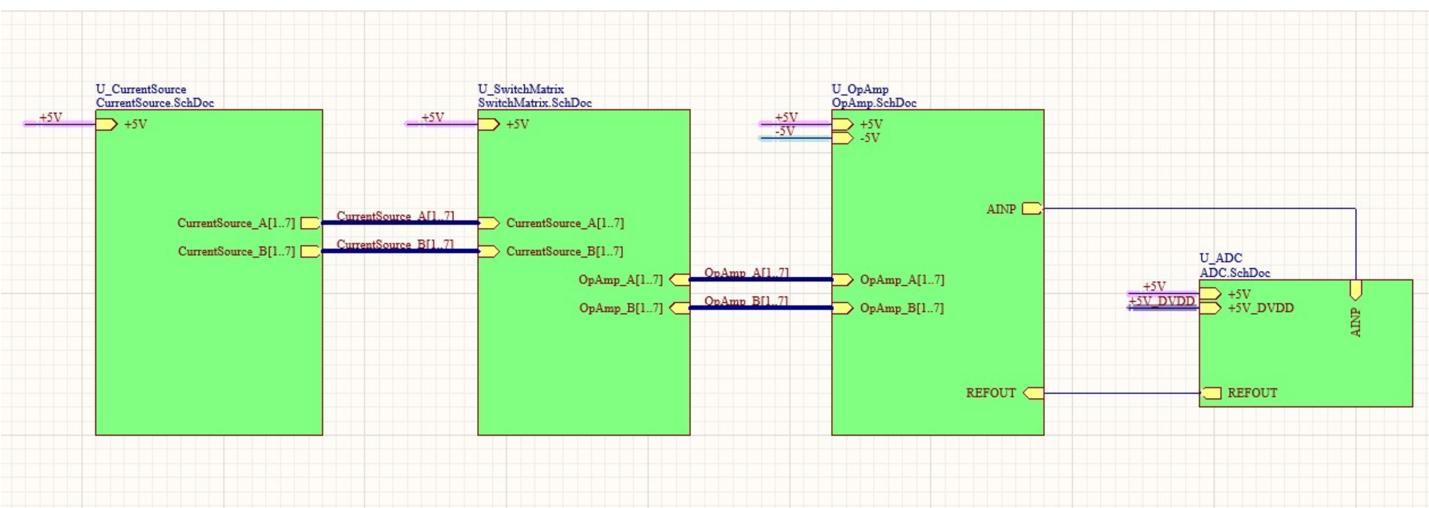

Figure 8: Main Measurement block sheet.

3.2.1 Microcontroller

An Arduino Due was chosen to control the board. It features up to 54 digital input/output pins; see pinout in Figure 9. This only covers most of the necessary communication interface connections with one extra shift register. Hence, the design remains simple. The Arduino also can be powered with a supply of 5V, provided directly using USB from the verification PC. The board is mated on top of the main PCB using through-hole Arduino to board male headers, which makes it easy to replace in case of any malfunction. Opting for an Arduino as well makes it more straightforward on the software development side.

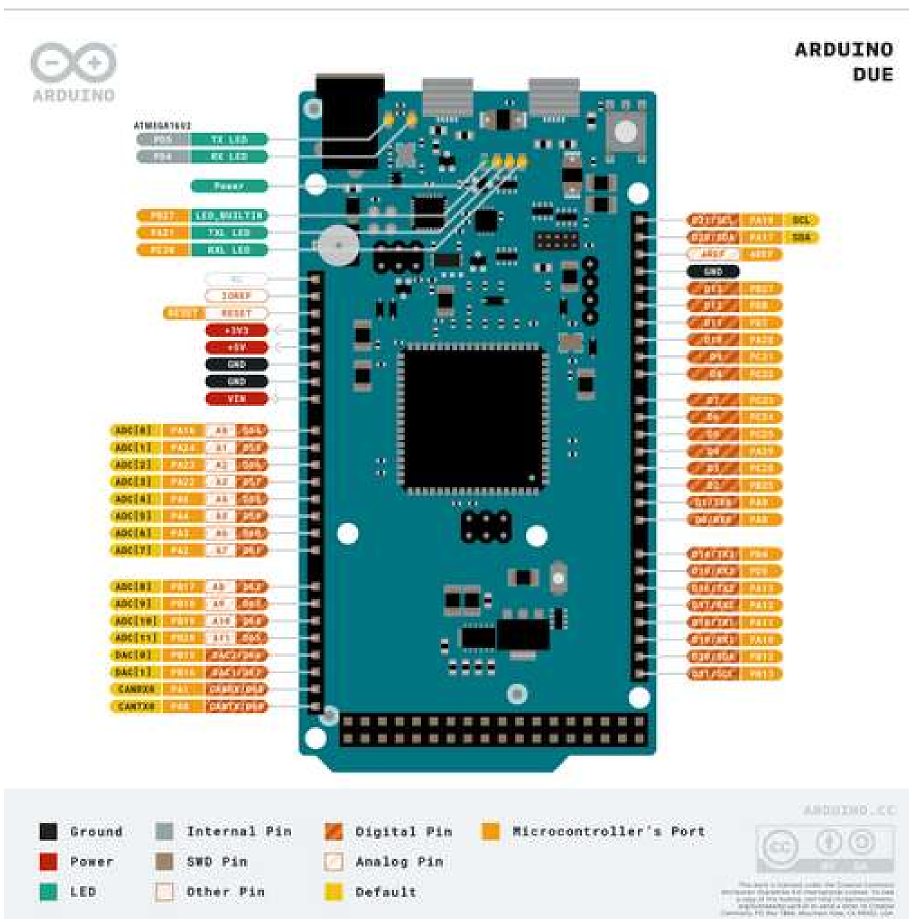

Figure 9: Arduino Due Pinout [11].

3.2.2 Analog Multiplexer

In the end product, ADG726 a 16:1 MUX from the same family as the ADG739 is used. Thanks to their low power dissipation, low resistance, and high switching speed, the ADG family of MUX/DEMUX ICs is designed to work well with low power high precision instrumentation, and data acquisition applications [12,1].

Expanding the capacity to up to 100 wires, and assuming that each wire/connection needed 4 associated pins, a total of 400 pins/switches were needed. Dividing the 400 by 64 pins available by using a pair of 2 ADG726, 6,25, or 7 pairs of MUXs is needed to meet the requirements.

Appendix 1 page 1 presents the schematic of one pair of MUXs, which is then repeated 7 more times.

Each ADG726 comes with 8 SPI connections that need to be routed to the microcontroller, in this case, the Arduino Due. A0, A1, A2, and A3, are 4-bit binary address lines. !CSA and !CSB are chip selects that can be connected for differential applications. Finally, !EN and !WR which are the enable and write pins respectively. [12,1.]

To simplify and minimize the number of SPI connections needed, a decision was made to connect all the !EN, A0s, A1, A2, and A3, of each MUX together. The !CSA and !CSB were tied together for differential output. However, each MUX maintains its unique chip-select pins and they are all routed separately to the Arduino.

Figure 10 is a timing sequence for latching the switch. To write to a specific switch !CSA and !CSB and !WR must be held low. !EN is always pulled low making all the switches enabled on power-on. The addresses are then changed, and the data is latched on the rising edge of !WR.

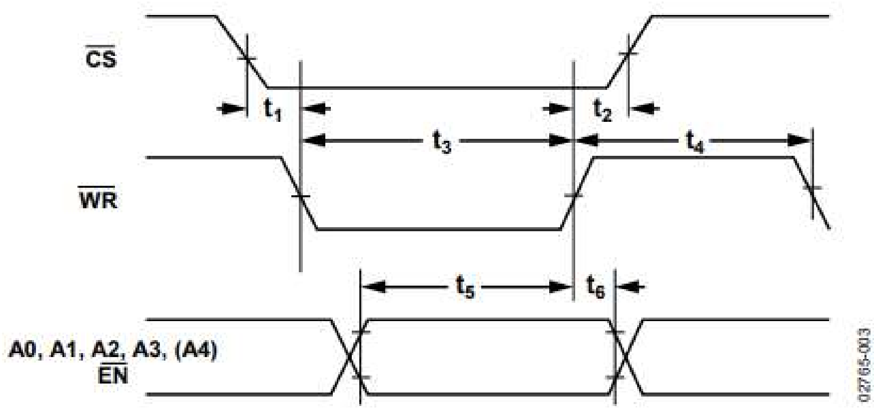

Figure 10: Timing Sequence for the latching of the switch [12].

3.2.3 Current Source

The Current source is one of the key elements in the system. A strict requirement of 10mA needed to be met. LM334M a 1uA to 10mA programmable current source is used. The design is quite straightforward, using only one resistor to set the output current.

The set resistor value can be calculated using Equation 2. From Figure 11, a ratio n equal to 1 to 2.5 can be assumed [13]. Based on this, the value of Rset is calculated at 22°C, and the closest value in the real world is chosen which equals 6.81 ohms. LM334 circuitry is shown in Figure 12.

$$Iset = \left(\frac{VR}{Rset}\right) * \left(\frac{n}{n-1}\right) \quad (1)$$

Where:

- VR is approximatively 214µV/°K.
- n is the ratio of Iset to I_bias defined by the component's electrical characteristics.

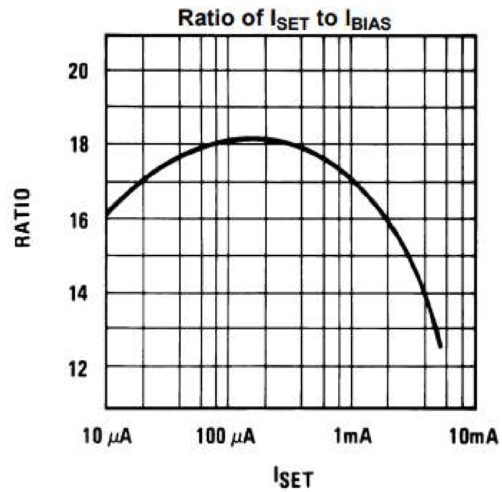

Figure 11: Ratio Iset to Ibias of Current Source [13].

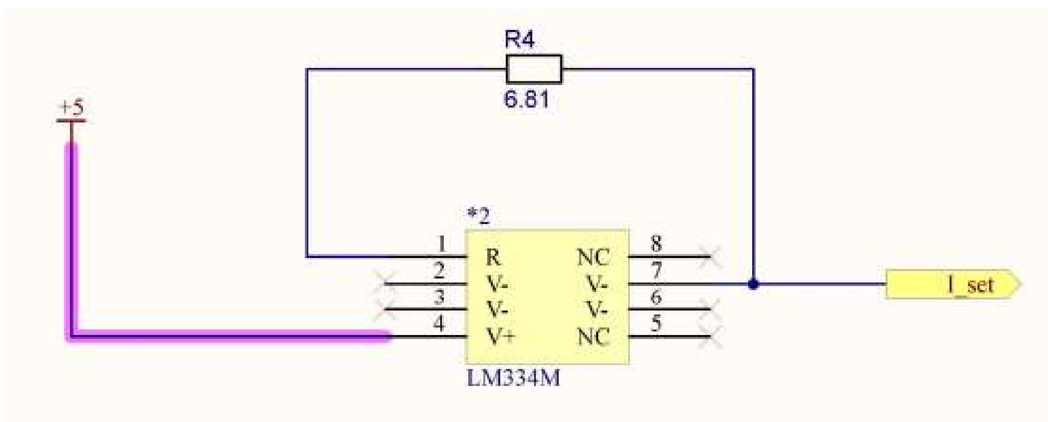

Figure 12: Current Source Circuitry.

3.2.4 ADC and Differential Operational Amplifier

The ADC and Differential operational amplifier are one of the main building blocks of this design. The measurement must be performed with high accuracy and fast while switching between all the connections to detect all types of faults.

INA118 Precision, Low-Power Instrumentation Amplifier, commonly used opamp was used in differential configuration connecting Vin+ and Vin- to the sense leads. The output of the latter drives the ADC analog input (see Appendix 1-3).

Moreover, the decision not to use Due's internal ADC is due to its low resolution. 12-bit resolution is not enough to reach the accuracy required by the requirement. Being able to measure down to 1mohm impedances demands at least higher resolutions. A choice ADS1210u a 24bits ADC was made. ADS1210U is a delta-sigma configurable 24 bits Analog Digital converter (See appendix 1-4) [14, 1].

Table 1 lists all the possible configurations that can be used by choosing different Xin clock frequencies or choosing whether or not to activate the Turbo mode at different rates.

DATA RATE (Hz)	X_{IN} CLOCK FREQUENCY (MHz)	TURBO MODE RATE	EFFECTIVE RESOLUTION (Bits rms)
60	10	1	19.5
60	5	2	19.5
60	2.5	4	19.5
60	1.25	8	19.5
60	0.625	16	19.5
100	10	1	18.0
100	5	2	18.0
100	2.5	4	18.0
100	1.25	8	18.0
100	0.625	16	18.0

Table 1: Effective Resolution vs Data Rate, Clock Frequency, and Turbo Mode Rate. (Gain set-ting of 1.) [14, 12].

3.2.5 Power Supply

Most Components on the board require a positive +5V supply except for the differential operational amplifier where a dual supply is needed. Moreover, the DVdd, digital supply of the ADC, and the AVdd analog supply needed to be separated, with the condition that the latter was always on before DVdd during the power-on sequence. Extra care was taken as well to follow proper grounding practice. For a single converter application, the digital plane needs to be joined to the analog plane with a moderate signal trace in the layout, with all digital signals referenced to it [14].

A higher-level overview of the power circuitry is displayed in Figure 13 as well as detailed circuits listed in Appendix 1, Figures 1-5, 1-6, and 1-7. Two MAX8881EYT50 LDOs to supply both +5V and Digital +5V. The output of the +5V LDO is connected to the digital +5V LDO!SHDN pin to ensure that the latter is turned on only after the +5V output is at a power-ok level.

The LMZ14203 a simple switcher is used for negative -5V generation.

Here Vin is supplied from a laboratory PSU and is defined in the limits of [6V,12V].

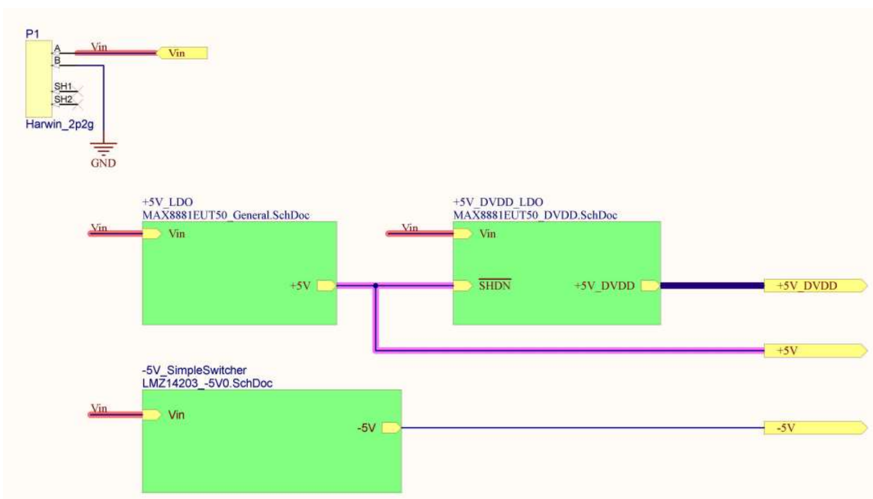

Figure 13: High-Level View of Power Circuitry.

3.2.6 LEDs

To elevate the user experience aspect, verification status LEDs are included on the board. 3 different LEDs with 3 different colors were assigned to different statuses:

- A pulsing Yellow LED to indicate that the verification is still in progress.
- A green LED to indicate that the harness has passed verification successfully.
- A Red LED to indicate that the harness has failed verification.

The LEDs are connected directly to Due's I/O pins and the series resistance needed to drive the LEDs was calculated using Equation 3. Assuming a supply voltage Vs of 3.3V a maximum current level If of 15mA, and a 2V forward voltage Vf for all the LEDs, resistors of 86.6 ohm were placed. See Figure 14.

$$R = \frac{Vs - Vf}{If} \qquad (3)$$

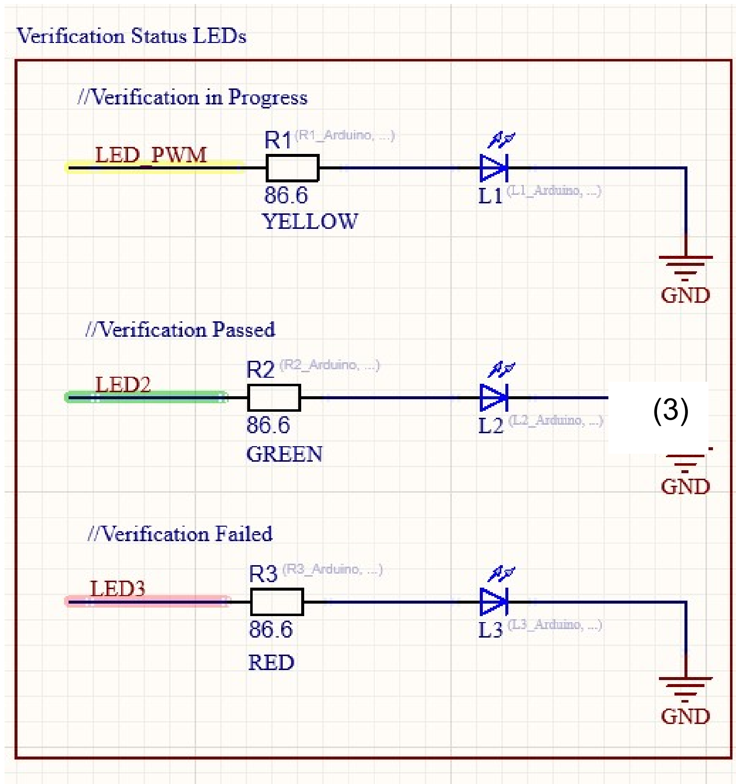

Figure 14: Status LEDs.

3.2.7 Board-to-Board Connectors and adapter board

Figure 15 demonstrates the TE connectivity fine pitch Board-to-Board header and receptacle connectors used to mate the Main PCB to the adapter board. The are 3 main reasons behind opting for this option of connectors. First, these connectors are designed to be easy to mate and also robust enough to withstand frequent plug in and out. Second, the multiple-point contact feature ensures firm mating and reliable electrical connectivity between the 2 boards. Last, they are small and do not occupy a large surface area [15.]

Two 100-position receptable connectors are used on the main board and two headers are on each adapter board. On the prototype, only 1 adapter board was designed and only a Harwin-type connector was used. It is planned to continue the design of other adapter boards once the first testing campaign is completed.

Figure 15: TE connectivity fine pitch Board-to-Board header and receptable connectors [16].

4 The PCB design and Software development

This section presents the methods and tools used to design the Harness verification PCB as well as a higher-level description of the software.

4.1 Hardware Design Process

Altium was used as the main software to design the PCB, and this was the first introduction to the tool. Before the kick-off of the design phase, a first basic introductory training was completed, and following that support was provided at all times by the thesis supervisor.

The initial schematic has become messy and difficult to read, requiring the implementation of Altium schematic architecture tools. However, this process proved to be challenging.
After a few trials, a hierarchical multi-channel architecture was eventually adopted for the main board. To facilitate the connection between the main board and the adapter PCBs, an Altium multi-board project was created.

In a hierarchical design a parent-child relationship is formed between the sheets and the ports are not connected directly one to the other but through sheet entries. There are no limits on how many hierarchical layers can be used. Therefore, the design can be divided into smaller pieces more logically, and connectivity between circuits can be followed easily from top to bottom or vice versa [17.]

A multi-channel design is also used when a repeated section of circuitry is present. The advantage of the latter is that the circuit only needs to be created once and then the software handles the expansion of all the components and connectivity by repeating it the required number of times [17.] Appendix 1-5 illustrates this practice in the expanded switch matrix.

4.2 A High-Level Description of Firmware and Automation

The software aspect consists of 3 different Layer:

- The FW which is the Arduino C++ code containing all the functions to control the switching of all the MUXs, handling data acquisition from measurement circuitry, and providing all the necessary digital outputs.

- Python automation to perform the full verification of harness assemblies. This includes the dictionary of all harness specs imported for RapidHarness, the main Python verification script which checks for all possible faults for each harness, compares measured impedances with user-defined criteria, and reports the results to WATS the internal test data management system.

- An additional layer is necessary to make the Arduino function available to the Python automation layer. For this, a cross-platform PyCmdMessenger library based on the CmdMessenger serial communication library is used to query send and receive data and commands to and from the Arduino.

5 Further Development

The Design went through several redesign phases either due to some mistakes throughout the process or due to components becoming obsolete.
One of the key learning in the project was the importance of ensuring the availability of the components used and more importantly that they are restocking normally.

The further development plan consists mainly of the first bring-up of the prototype with SW tests. The idea would be to gather as much statistical data as possible by introducing different test conditions and harnesses under test and recording the variation in impedances recorded and also in the functional behavior of Hardware and reliability of Software.

A 3D-printed support structure to prevent the main PCB from bending every time an adapter board is plugged in and out would be beneficial as well. Moreover, more adapter boards introducing the other types of connectors used in harness assemblies must be designed. As an extra a GUI can be made as well, but it is not necessary nor a priority at the moment.

6 Conclusion

The thesis project proved to be an extensive undertaking that involved aspects of Hardware design and software development. It was quite a slow learning curve, however many learnings about the design flow, instrumentation electronics, and embedded systems were acquired.

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Appendix 1: Harness Verification Jig Main Board Schematic Sheets

This Appendix lists the schematic sheets and circuits of the Harness verification jig main board in the order they are mentioned in the document.

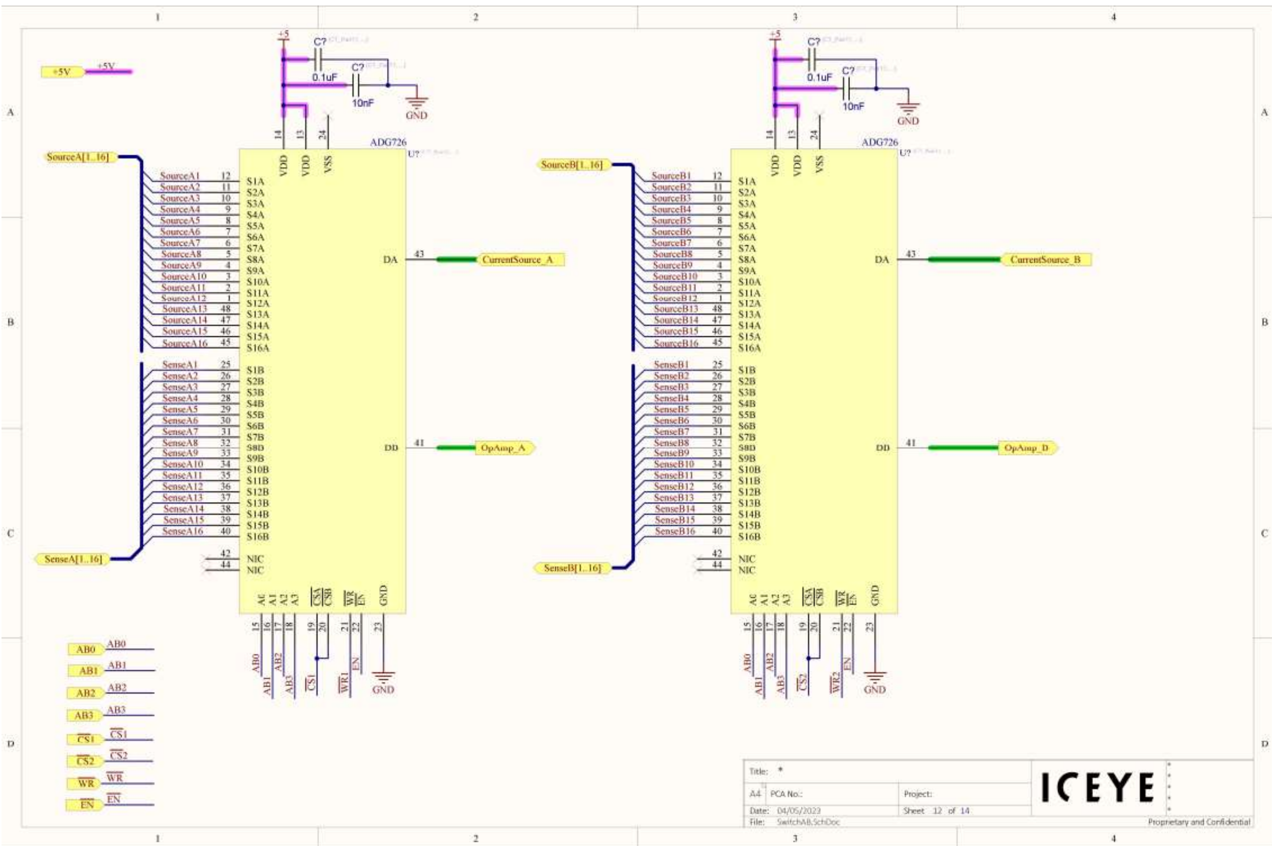

Figure 1-1: Switch Pair Schematic

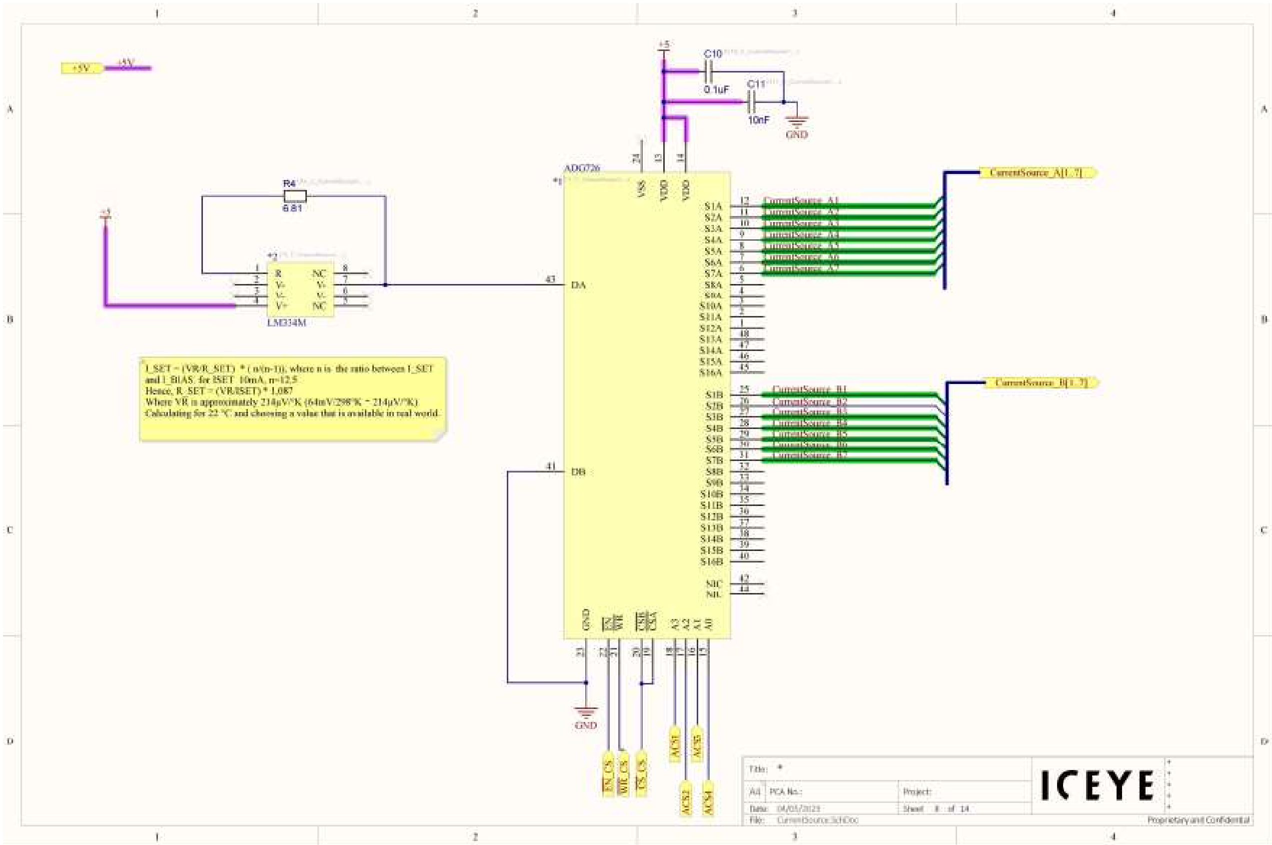

Figure 1-2: Current source schematic

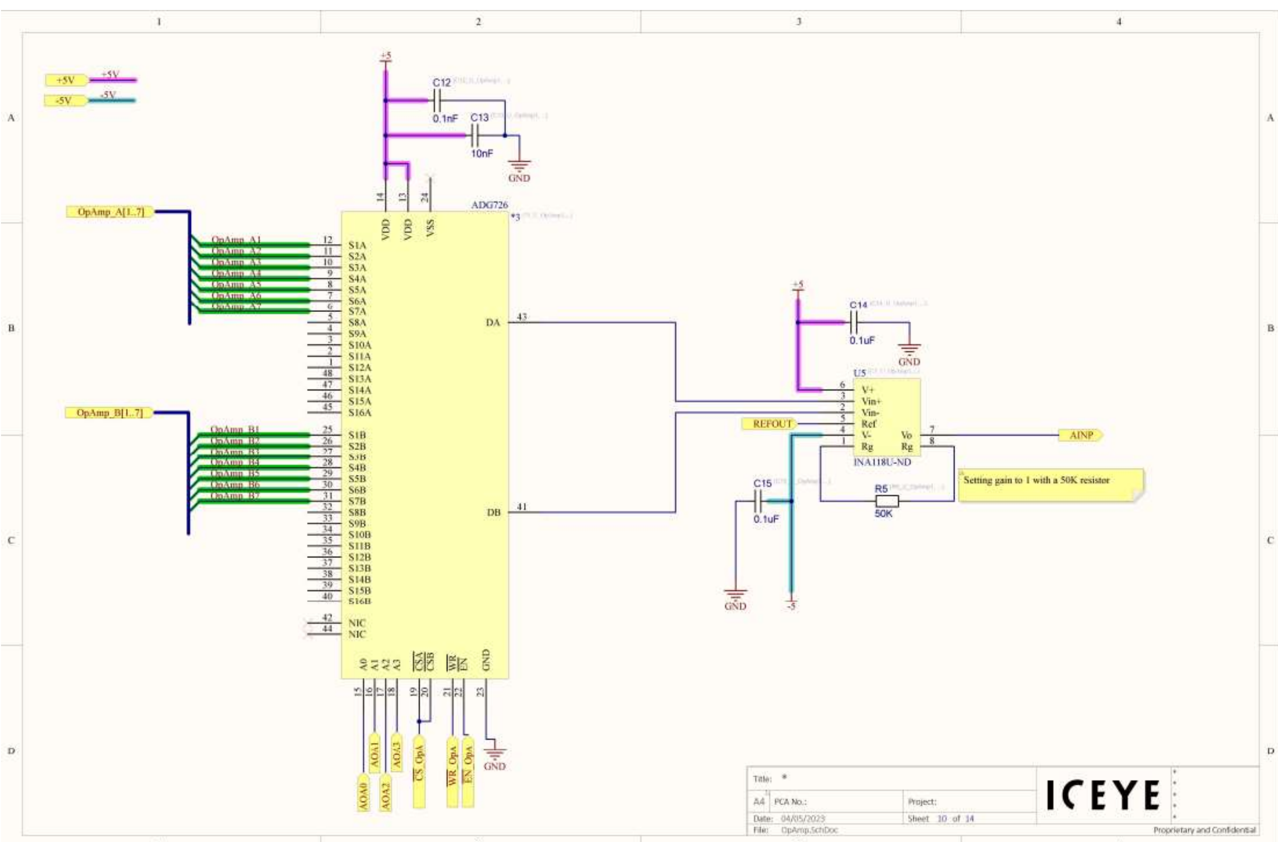

Figure 1-3: Differential opAmp Schematic

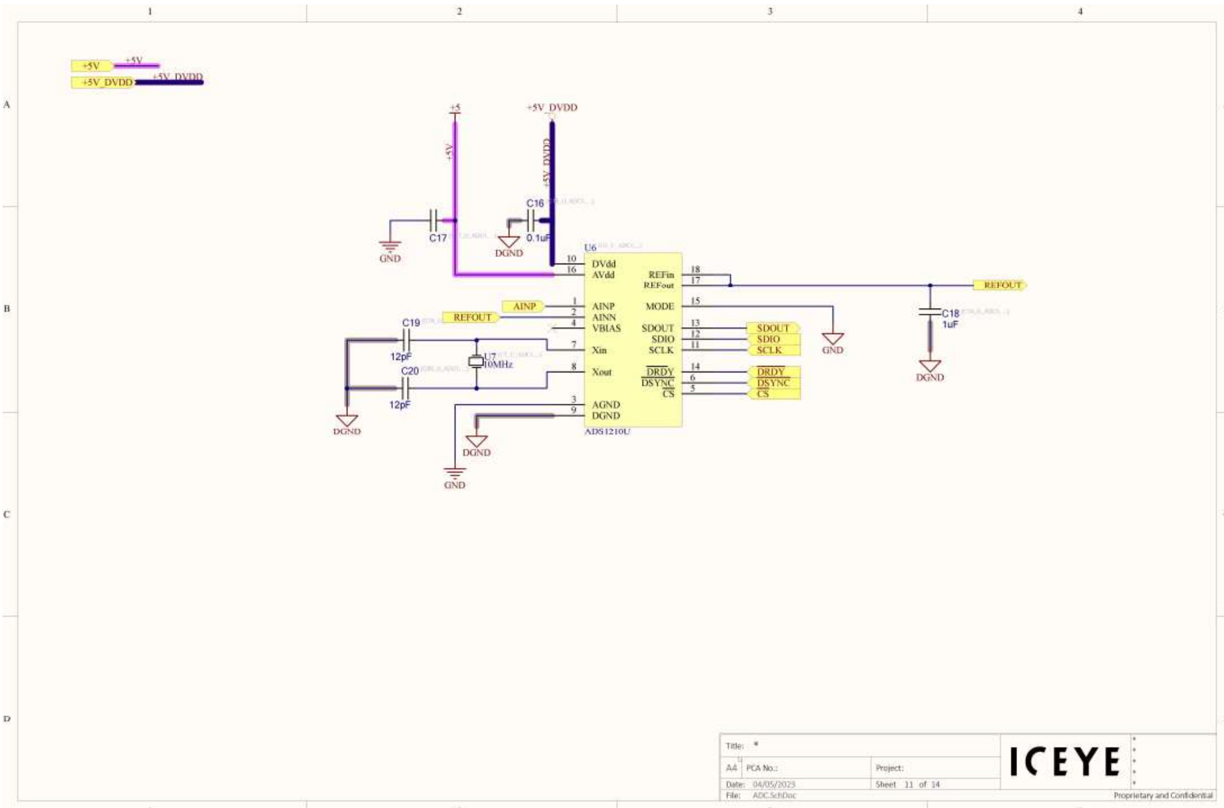

Figure 1-4: ADC Schematic

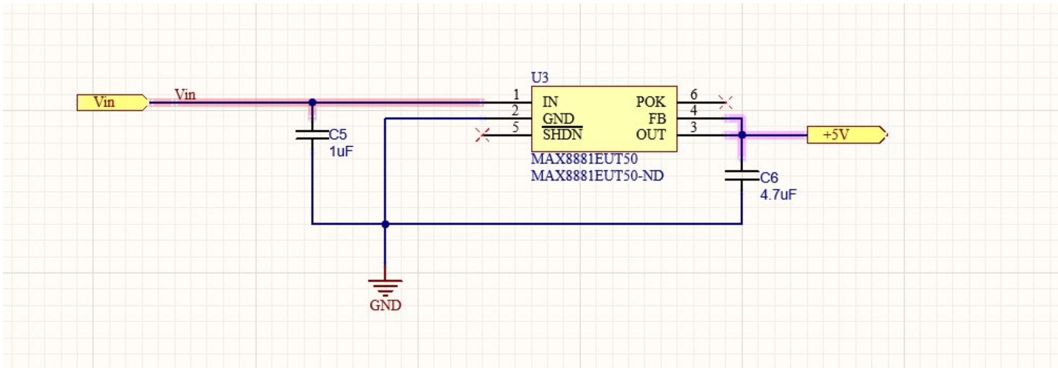

Figure 1-5: +5V LDO Circuit

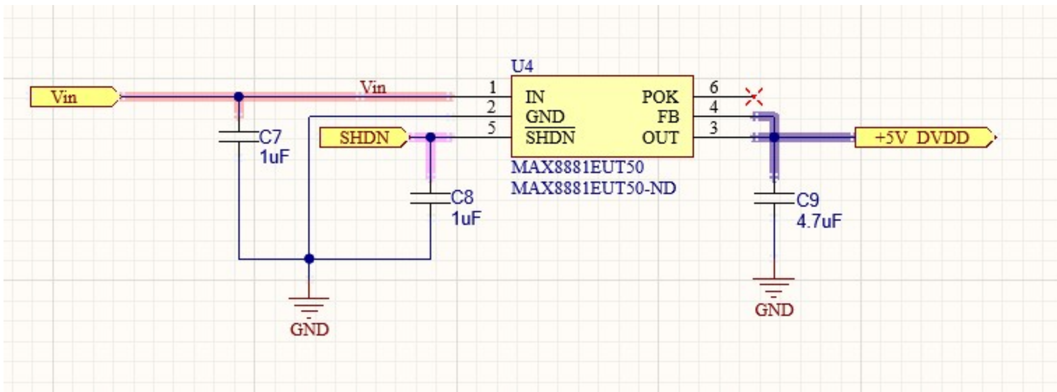

Figure 1-6: +5V Digital Supply Circuit

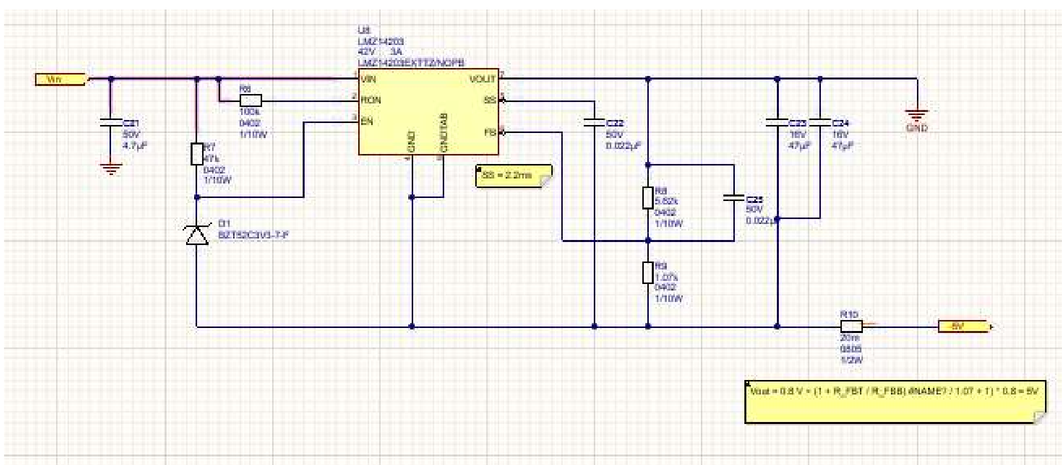

Figure 1-7: -5V Simple Switcher Circuit

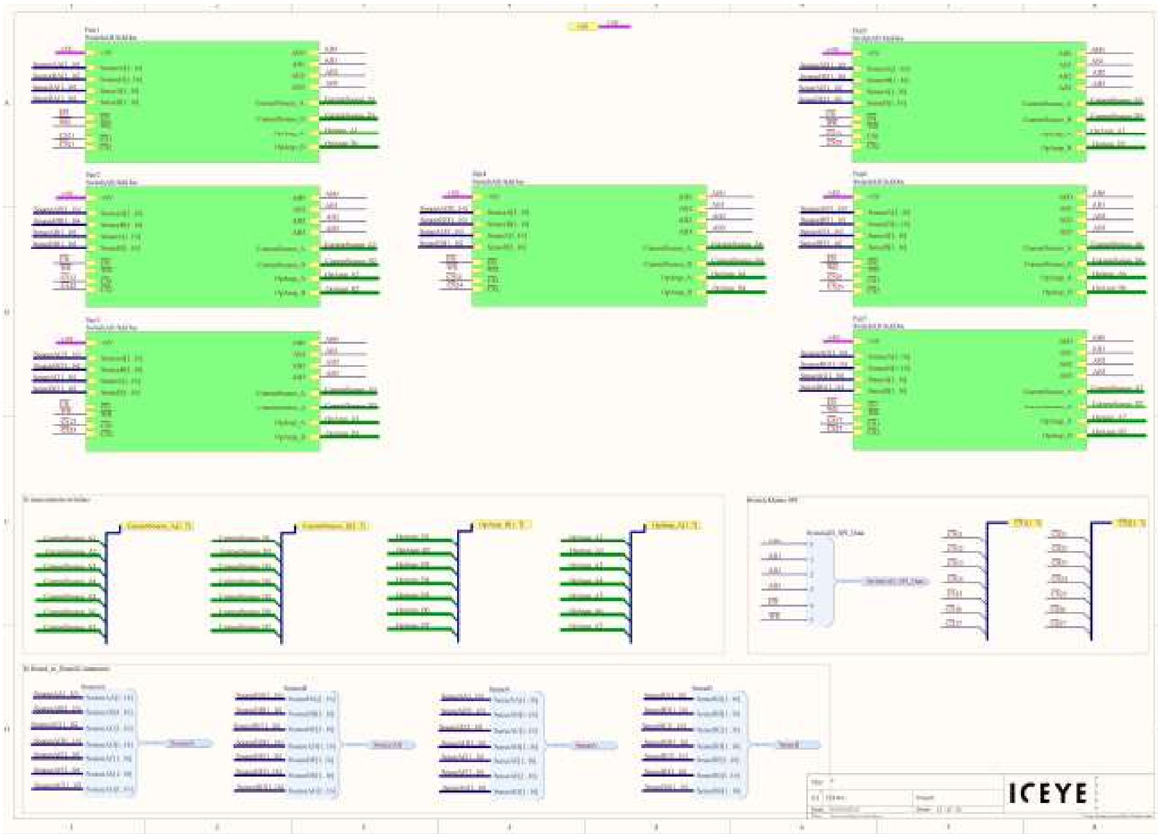

Figure 1-9: Expanded Switch Matrix Schematic