Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

Sneltvedt, Trym

Microcontroller Breakout Board for Formula Student Race Cars

Master's thesis in Electronics Systems Design and Innovation
Supervisor: Bjørn B. Larsen
July 2020

NTNU
Norwegian University of
Science and Technology

Sneltvedt, Trym

Microcontroller Breakout Board for Formula Student Race Cars

Master's thesis in Electronics Systems Design and Innovation
Supervisor: Bjørn B. Larsen
July 2020

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

NTNU
Norwegian University of
Science and Technology

Abstract

Embedded control electronics designed for Formula Student competitions must improve every season to keep up with the competition. Annual redesigns require extensive development, manufacture, and testing time and will inevitably introduce errors to the designs. This project extracts a SAM microcontroller, CAN-FD transceivers, and other commonly used components to a reusable breakout board. Modularizing the systems reduces the amount of circuitry which needs a redesign. Breakout boards can be used across multiple seasons, reducing manufacturing time, make knowledge transfer more efficient, and increase trust in the boards. The standardized layout and ability to test different parts of the system individually makes testing easier. Testing shows the board to be compatible with current software and more robust to faults, especially over-current and over-voltage, than previous systems.

Innvevde kontrollsystemer utviklet for Formula Student-konkurranser er avhengige av å kontinuerlig forbedres for å holde tritt med konkurransen. Å redesigne systemene årlig krever at man setter av tid til utvikling, produksjon og testing, og det introduserer alltid nye feil på designet. Dette prosjektet går ut på å hente ut en SAM mikrokontroller, CAN-FD transceivere og andre nødvendige kretser og plassere det på en egen modul. Å modularisere systemer reduserer produksjonstid, effektiviserer kunnskapsoverføring og øker tilliten til systemene. Det standardiserte utlegget og muligheten for å teste de ulike modulene individuelt gjør testing enklere. Testene gjort som en del av dette prosjektet viser at modulen er kompatibel med programvaren fra nåværende systemer og mer robust mot brukerfeil, spesielt overstrøm og overspenning, enn tidligere systemer.

Terms

MCU Microcontroller unit

SoC System-on-Chip

MPSoC Multi-processor System-on-Chip

SoM System-on-Module

IC Integrated circuit

SMD Surface-mounted device

PCB Printed circuit board

ESD Electrostatic discharge

FS Formula student

EV Electric vehicle

DV Driverless vehicle

SPI Serial peripheral interface

I^2C Inter-integrated circuit

UART Universal asynchronous receiver-transmitter

USB Universal serial bus

Contents

Chapter 1

Introduction

1.1 Project scenario

This report details the design of a microcontroller unit (MCU) *breakout board* in cooperation with Revolve NTNU, a student organization dedicated to creating electric race-cars for the international Formula Student (FS) competitions. Since 2018, Revolve NTNU has been creating two race cars every season, one electric vehicle (EV), and one driverless vehicle (DV). Creating a race car from scratch is a time-consuming and expensive process, leading to the team creating a DV by retrofitting an EV from a previous season with sensors, actuators, and control systems, which allows it to operate without a human driver.

Race cars competing in Formula Student competitions are subject to strict technical inspections, determining whether the vehicles conform to safety rules. If a race car passes inspections, it is allowed to compete in a range of static and dynamic events.

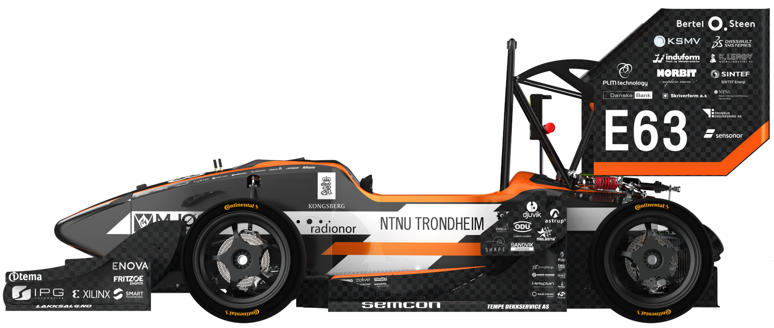


Figure 1.1: Revolve NTNU Nova, EV from the 2019 season.

Creating and maintaining electric race cars is a challenge, made even more difficult by the fierce competition with other skilled teams. Embedded electronic control systems are often remade annually, due to technical innovations, increased experience within the team, and changes to the competition rules. While having team members remake previous systems every season does give each member a better understanding of the systems, it comes at a cost. Design, manufacture, and testing are done in-house by members, meaning the cycle of remaking complicated electronics takes up much time. It also inevitably introduces errors to the design, an example being a 2.2Ω resistor mistakenly switched with a 2.2kΩ resistor in the supply filter for an oscillator. This error led to failures of several subsystems, taking up several weeks of debugging and testing for several members before they found the error. While mistakes like this one can be avoided by improving routines for reusing previous designs and more thorough design reviews, the time and money spent manufacturing and testing complicated every season still is a significant time sink.

1.2 Project description

1.2.1 Project requirements

The requirements put forth by Revolve NTNU for this project are as follows:

> The candidate shall develop a breakout board for the ATSAME70 MCU currently in use at Revolve NTNU. The breakout board must support at least the same number of each interface as is currently available. The main project goal shall be reducing the development time for future embedded electronics projects. Secondary project goals shall be reliability and standardization, coinciding with the focus areas of the Embedded Electronics group.

1.2.2 Scope

Hardware design of a breakout board PCB containing commonly used circuitry is the main focus of this project. Additionally, the design of support PCBs aiding in testing and working with the breakout board is covered.

The software needed to operate the breakout board is not a part of this project.

1.2.3 Layout

Chapter 2 - Background covers the most important concepts and theory used in the implementation phase on the project. Additionally, we look at the current systems at Revolve NTNU, choosing the most important aspects and having them in mind for when we develop the requirements for the system.

Chapter 3 - Implementation the formation of requirements for the module based on chapter 2. The requirements serve as a foundation for the system architecture and design choices also detailed in this chapter.

Chapter 4 - Results goes further into detail on verification and validation of the system. Finally, we discuss the module in regards to its requirements.

Chapter 2

Background

2.1 Embedded systems

Embedded systems are a subgroup of digital systems, designed to operate within a system (often mechanical), performing a specific task. Like most digital systems, embedded systems typically consist of a central processing unit (CPU) which gathers data through communication interfaces and sensor peripherals. The CPU performs logical and arithmetic operations on the data and feeds the results to other systems or directly to actuators. In embedded systems, the CPU commonly comes in the form of an MCU, microprocessor unit (MPU), or System-on-Chip (SoC).

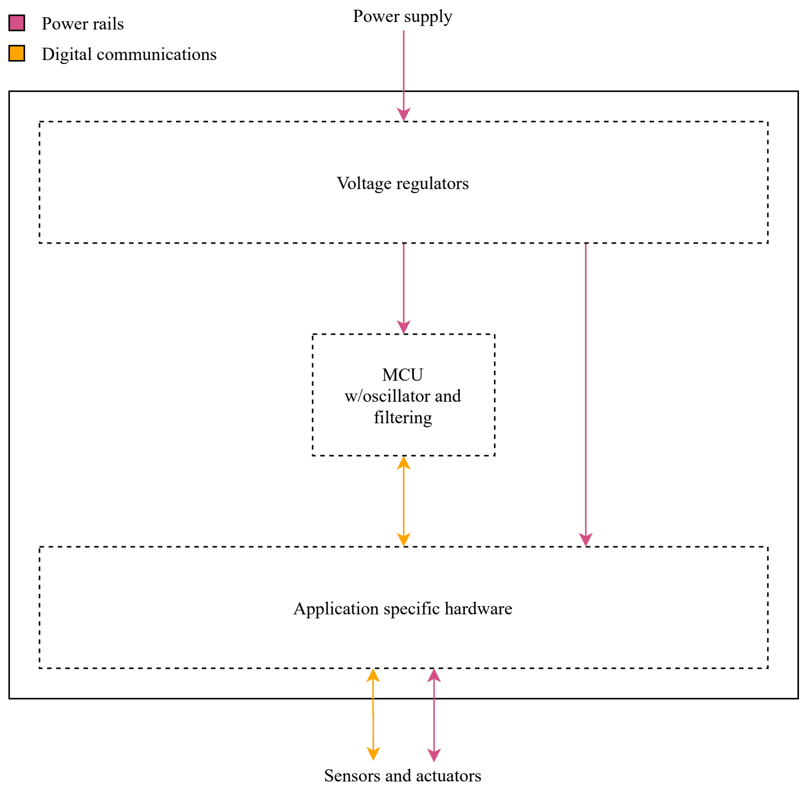


Figure 2.1: Basic embedded system architecture.

Additionally, a power stage is commonly present in embedded systems. The power stage supplies the integrated circuits with the desired voltage and current. This is illustrated in figure 2.1.

2.2 Microcontrollers

The computer architectures used in nearly all modern computers separate memory from control logic and arithmetics. It is common to see the processing unit and memory separated into discrete components or modules on larger computer systems. While this increases the flexibility and adaptability of the system, it also increases the complexity of the hardware design. Specifically, memory is generally a bottleneck for computers when it comes to performance, and to get decent speed on external memory, it requires large buses for parallel data transfer and high-speed signaling. High-speed signaling requires careful attention to electrical interference on and from other circuitry.

Microcontroller units (MCUs) are typically used for simpler digital systems where less memory is needed. A MCU integrates processing unit, working memory, program memory, and digital peripherals into a single integrated circuit. The peripherals often include communication interfaces, analog-to-digital converters, and general-purpose input/output (I/O) pins used to read electric switch states or drive simple circuitry like transistors and indication LEDs.

Microcontrollers offer digital designers a high degree of flexibility and simplified hardware design, at the cost of processor throughput and available memory.

2.2.1 Peripherals pin mapping

The number of peripherals available on the specific microcontroller varies, but more often than not, a MCU has more peripheral signals than can be used at the same time. Multiplexing on the individual pins allows fine-grained control over the available peripherals. The SAM S70/E70/V70/V71 family of MCUs can have as much as five different peripherals signals available on a given pin, as well as peripherals that may make their signals available on multiple pins.

Deciding which peripherals are necessary is, therefore, an essential part of any hardware design project using a microcontroller. This specific system is thought to both operate by itself and as a core for other systems, meaning as much functionality as possible should be available to the user.

2.3 Breakout boards

A breakout board is one or more subcircuits extracted out into a dedicated PCB, a common way of *modularizing* an electronic system. The convention used in this project is calling the base system to which the breakout board is connected, the *carrier board*. Figure 2.2 shows the basic structure of a modular electronic system.

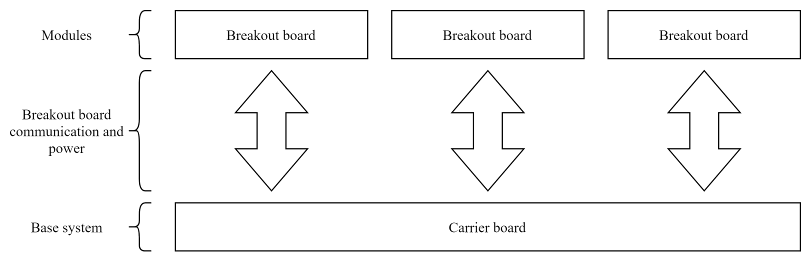


Figure 2.2: Generic modular hardware system and terminology used in this project.

Modular systems have several advantages. Separating faulty systems into smaller units makes fault localization easier, and replacement only needs to be done for the faulty module. They are more *maintainable* and allows for more reuse. Allocating advanced subsystems to breakout boards reduces the cognitive load for developers making carrier boards and allows different modules to be manufactured with different technologies, like tighter tolerances and more copper layers, reducing the total cost.

Modularization also enables *polymorphism*, the ability for a system to be adapted to the current application by mixing and matching modules based on their functionality.

2.4 Current systems

2.4.1 Architecture

Since this project aims to create a breakout board that can serve as the core component of future systems at Revolve NTNU, a decent overview of the current systems (and concepts for the coming seasons) is needed. Figure 2.3 shows the basic structure of embedded systems at Revolve NTNU. All systems at Revolve NTNU based around a MCU shares this structure, and it will be the foundation of the work done in this project.

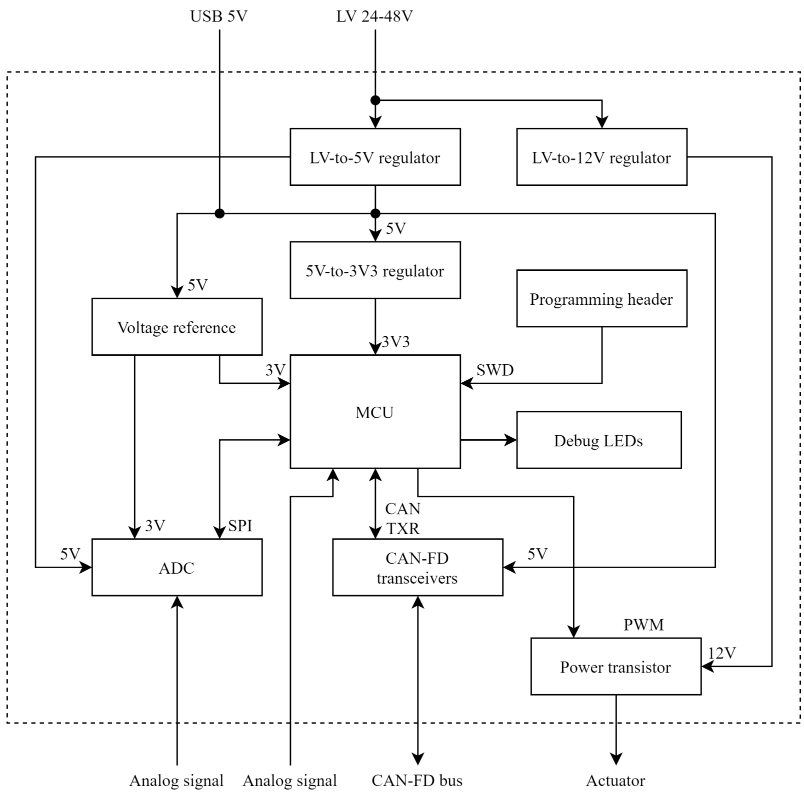


Figure 2.3: Typical embedded system architecture at Revolve NTNU.

2.4.2 MCU

The MCU used at Revovle NTNU is the Microchip ATSAME70N21B [1]. An ARM Cortex-M7 based MCU with support for CAN-FD, capable of operation at up to 300MHz.

The specification states that the breakout board must use the same MCU as most current control systems at Revolve NTNU, the ATSAME70N21B. It is safe to assume that this specification entails two things, current software must be compatible with the breakout board (at worst require very little modification), and to keep the same number and types of peripherals.

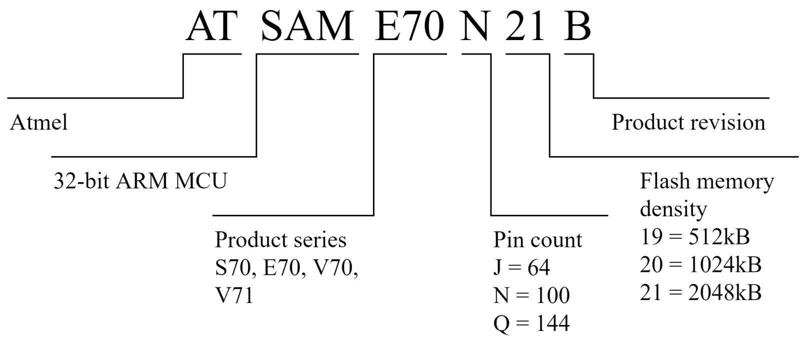


Figure 2.4: SAM S70/E70/V70/V71 family naming breakdown [1, p. 16].

Interchangeable MCUs

Both these requirements can be met while changing the MCU *variant*, so it is interresting to investigate our options. The ATSAME70 product series is a member of the SAM S70/E70/V70/V71 family of MCUs from Microchip (previously Atmel). The MCU family naming scheme can be seen in figure 2.4 The different products in the family has different peripherals and comes in multiple configurations, but they are built around the same ARM Cortex M7 CPU and core circuitry, making porting of software almost trivial.

The specific features available to the E70 series should be looked into. Table 2.1 shows the main differences between the different product series.

Table 2.1: Functional differences between product series in the SAM E70/S70/V70/V71 family.

Product series	CAN-FD interfaces	Ethernet	Automotive rating (AEC-Q100)
E70	2	Yes	No
S70	0	No	No
V70	1	No	Yes
V71	2	Yes	Yes

As CAN-FD is heavily used at Revolve NTNU, only the E70 and V71 series are viable options for the breakout board. The V71 features all the same peripherals as the E70, in addition to being automotive rated (AEC-Q100 grade 2). It is noticeably more expensive however, so the cheaper E70 series may be used, although V71 is to prefer.

To maintain compatibility with current software, the 2048kB flash memory variant should be used.

In regards to the pin count the 144-pin variant should be used as this increases the number of peripherals available to the developer, figure 2.5 shows the current use of communication peripherals in use on the different systems.

To accommodate field repairs, the LQFP package with exposed pins shall be used. Although this comes at the cost of much larger footprint compared to the TFBGA package, it also simplifies PCB layout and makes a 4 layer PCB an option.

2.4.3 Peripherals

A plethora of communication interfaces and peripherals are used in Revolve NTNUs embedded systems. Figure 2.5 illustrates which peripherals are used and where.

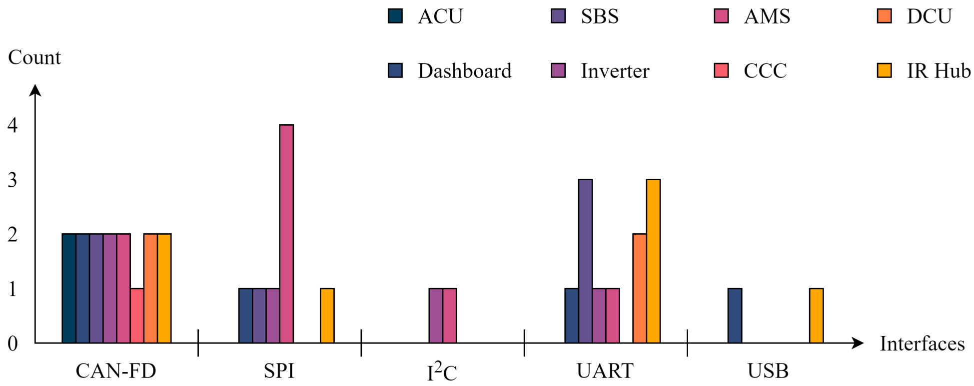


Figure 2.5: MCU peripheral usage among current Revolve NTNU systems.

What follows is a short description of the different peripherals.

CAN-FD

Controller Area Network (CAN) is a multi-master half-duplex bus communication protocol. The protocol is designed for automotive electronic systems, and it is based around differential signaling on a pair of twisted copper cables, making it robust to electrical interference. Messages are referred to as *frames* in the CAN protocol.

CAN Flexible Data-rate (CAN-FD) is an extension to the CAN protocol, allowing larger frame sizes and transmission speeds.

CAN and CAN-FD typically require a discrete transceiver IC because of the differential signaling.

SPI

Serial Peripheral Interface (SPI) is a synchronous, full-duplex (simultaneous two-way) communication protocol commonly used in embedded systems for communication between ICs. Communicating systems operate as either a master or a slave. One SPI interface should consist of one master and at least one slave. Slaves are selected using a dedicated select signal.

Quad SPI (QSPI) is a variation on the SPI protocol where two extra signal lines are introduced. When the full-duplex is not needed, data can be transmitted over both the original signal lines at the same time as the two new lines.

I^{2}C

Inter-integrated circuit (I^{2}C) is a synchronous, half-duplex (two way, taking turns) communication protocol used in embedded systems. It is a master-slave system, but unlike SPI a separate slave select signal is not needed as messages are addressed to individual slaves. This makes I^{2}C only require two signal lines for operation, data, and clock.

UART

Universal asynchronous receiver-transmitter (UART) is a simple, asynchronous, full-duplex communication protocol. It only needs two signal lines, TX to transceive and RX to receive. It is commonly used for communication with personal computers, although a USB bridge is commonly needed for newer computers.

USB

Universal Serial Bus (USB) is a multi-purpose interface for data and power transmission, which easily interconnects with personal computers. Hardware for Full-speed USB 2.0 is present on the ATSAME70/V71. Despite being available on the MCU, USB is rarely used by embedded systems at Revolve NTNU for anything other than power delivery. The high complexity of the USB protocol is likely the reason.

PWM

Pulse width modulation (PWM) is a technique for approximating an analog signal on a digital line by rapidly switching signal between high and low. A PWM period is given, keeping the signal low for a portion of the period, then setting it high for the remainder of the period. This is repeated periodically. How much of the total time the signal is high is referred to as the *duty cycle* of the PWM.

2.4.4 Isolated CAN-FD

As a FS team continually working to improve their designs, Revolve NTNU is always looking into concepts that can be used in the future. The breakout board designed in this project should conform to the plans for future embedded systems solutions. The most important concept for the next season is *isolated CAN-FD interfaces*.

Isolated communication interfaces ensure no reference between the voltage rails on either side of the signal. The main advantage of isolated communication is the negation of *ground loops*, being the ground potential being slightly different throughout the system, which will make currents flow through though the ground potential rail, potentially creating electric fields and inducing noise in other signal lines.

For added flexibility, the CAN-FD transceivers should be optional. Being able to disable on-board transceivers might be necessary for some systems because of placement within the vehicles.

2.4.5 Power stage

Table 2.2 shows the MCU, power supplies and interfaces currently in use at Revolve NTNU. It is commonly a set of voltage regulators stepping a 24-48V LV down to votlages used by ICs. In regards to safety mechanisms, a Zener diode acts as both ESD protection and overvoltage protection, and a single inline diode protects against reverse current.

Table 2.2: Features of embedded systems at Revolve NTNU as of the 2020 season.

System name	MCU	Power supplies	# CAN-FD	# SPI	# I^2C	# UART	# USB
Autonomous Control Unit	ATSAME70N21B	3V3, 5V	2	0	0	0	0
Dashboard	ATSAME70N21B	3V3, 5V, 12V, 18V	2	1	0	1	1
Sensor Broadcasting System	ATSAME70N21B	3V3, 5V, 12V	2	1	0	3	0
Inverter Control	2x ATSAME70N21B	3V3, 5V, 12V, 15V, -15V	2	1	1	1	0
Accumulator Management System	ATSAME70N21B	3V3, 5V	2	4	1	1	0
Cooling Control Card	ATSAME70N21B	3V3, 5V, 12V	1	0	0	0	0
Damper Control Unit	ATSAME70N21B	3V3, 5V, 12V	2	0	0	2	0
IR Sensor Hub	ATSAME70N21B	3V3, 5V, 2V6, 24V	2	1	0	3	1
Vehicle Control Unit	Xilinx Zynq-7000	5V	5	0	0	2	0

2.4.6 Design space

Several factors must be taken into consideration when selecting connectors for embedded modules. The module is thought to be easily replaceable in case of a nonrecoverable fault. This makes soldering the module to the carrier board a less attractive solution, it is more feasible to use a board-to-board connector.

An important parameter when selecting the connector is the physical restrictions on the embedded systems, often called *design space*. Most embedded systems at Revolve NTNU are located within rectangular boxes made up of carbon fiber.

Table 2.3: Revolve NTNU embedded systems design space as of 2020.

System name	Width	Height	Depth
DCU	70mm	24mm	115mm
SBS	50mm	24mm	150mm
CCC	86mm	24mm	140mm
BSPD	49mm	24mm	90mm

From table 2.3 we see that all boxes has a height restriction of 24mm. With a vertical stack-up, this sets restrictions to the stacking height of the board-to-board connectors. The stack-up of carrier board and breakout board, shown in figure 2.6 illustrates the different heights that make up the total stack up. From the figure we can create the equation for the stack-up height

$$h_{stackup} = h_{top} + h_{PCBmodule} + h_{mezzanine} + h_{PCBcarrier} + h_{standoffs}$$

The total stack-up must not exceed the maximum height h_{max}, making for the following relation.

$$h_{stackup} \leq h_{max}$$

The standoffs ordinarily used by Revolve NTNU are Essentra LCBSBM-4-01A-RT [11], having a standoff height of $h_{standoffs} = 6.4$mm. The breakout PCB height is $h_{PCBmodule} =$ 1.6mm, the standard

The standoffs used to mount the PCB to the bottom of the casing leaves a gap of 6.4mm between the case bottom and PCB. The thickness of PCBs can be specified when manufacturing, While this can be decreased, it will affect the mechanical robustness of the system, and should be avoided. The height of the tallest component on top of the module gives us the last restriction. The module is thought to have a horizontal Molex DuraClik 5 pin connector for CAN-FD and termination. The height of this connector is 6.4mm. With this information, we can calculate the maximum stacking height of the connectors. $h_{connector(max)} = h_{max} - h_{top} - 2h_{PCB} - h_{standoff} = 24mm - 6.4mm - 2 \cdot 1.6mm - 6.4mm = \underline{8mm}$.

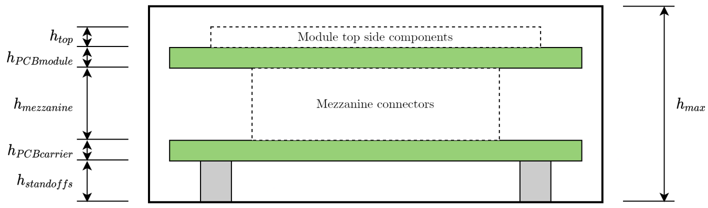


Figure 2.6: Breakout and carrier stack-up height

Another important factor is the maintainability of the connector. This encompasses how easily the connector can be soldered and desoldered. To accommodate soldering in settings where minimal equipment is available, the pin pitch (center-center distance between neighboring pins) should not be less than 0.5mm.

2.5 Reliability engineering

In regards to reliability and maintainability engineering, Alessandro Birolini's book *Reliability engineering: theory and practice* [2] serves as the core reference for this project.

2.5.1 Concepts

Reliability The probability a system has of performing its function for a stated time.

Failure A systems deviation from the required function.

Fault The underlying reason for a failure.

Error A mistake that led to the creation of a fault.

Reliability

This thesis aims at a practical approach to reliability, but that does not make reliability theory redundant. The real challenge in employing reliability is adapting the theory in a meaningful way. We will start by looking at some basic reliability theory.

2.5.2 Parameters influencing failure rate

When considering the reliability of the breakout board, determining what parameters are detrimental to the lifetime of electronic components is of concern.

Table 2.4: Dominant parameters in regards to component failure rate [2, p.32]
.

Component type	Most important parameter(s)
Integrated circuits (ICs)	Junction temperature
Bipolar junction transistors (BJTs)	Junction temperature, power stress
Field effect transistors (FETs)	Junction temperature, power stress
Diodes	Junction temperature
Optoelectronics	Junction temperature
Resistors	Ambient temperature, power stress
Capacitors	Ambient temperature, voltage stress, application
Inductors, transformers	Ambient temperature
Relays, switches	Ambient temperature, contact construction
Connectors	Ambient temperature, contact construction

Table 2.4 indicates that temperature is a critical parameter for all electronic components (junction temperature θ_J for semiconductors and ambient temperature θ_A for passives). This makes it clear that managing temperature should be a priority when designing the module.

2.5.3 Junction temperature

For ICs, junction temperature θ_J is more important for reliability than ambient temperature θ_A. While keeping θ_J close to θ_A is optimal, this is unrealistic for certain ICs, for example linear voltage regulators. For these cases we use the following rule:

$$\theta_J < 100°\text{C}$$

Calculating the junction temperature for an IC is done using equation 2.1.

$$\theta_J = \theta_A + R_{JA}P \tag{2.1}$$

R_{JA} is the thermal resistance of the component, given in degrees Celsius per watt $[\frac{°\text{C}}{\text{W}}]$. It depends mostly on the component packaging and should be available in the datasheet for applicable ICs. P is the effect dissipated by the IC, given in watts.

2.5.4 Derating

Derating is one of the more common techniques employed to increase reliability.

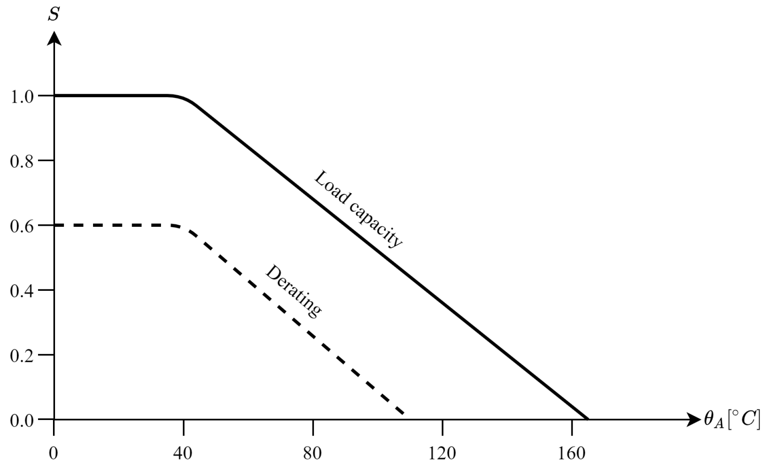


Figure 2.7: Stress factor as a function of ambient temperature, the derating curve [2, p.33].

As shown in figure 2.7, derating is merely applying a lower load to a component than the rated maximum. The stress factor S on the y-axis in the figure is defined in equation 2.2.

$$S = \frac{\text{applied load}}{\text{rated load at 40°C}} \tag{2.2}$$

The derating stress factor should be selected with regards to the operating conditions and required reliability rating of the system. For example, there are derating standards for aerospace and military systems. For this project, the stress factors in table 2.5 are be used.

Table 2.5: Derating stress factor S for room temperature 20°C $\leq \theta_A \leq$ 40°C [2, p.145].

Component type	Power	Voltage	Current	Temperature	Frequency
Resistor	0.6			0.8	
Ceramic capacitor		0.5		0.5	
Gen. purpose diode		0.5	0.6	0.7	
Zener diode	0.6			0.7	
Transistor		0.5	0.7	0.7	$0.1f_T$
IC (linear)		0.7	0.8	0.7	0.9
Voltage regulator			0.7	0.7	
IC (digital)			0.8	0.7	0.9
Inductor	0.5				
Switch			0.7	0.7	0.5
Connector		0.7	0.6	0.8	0.5

2.5.5 Automotive electronics qualifications

There exists a vast number of international rating standards. Organizations or councils usually define these standards. When talking about automotive electronics, the Automotive Electronics Council (AEC) is especially relevant. AEC was founded in the 1990s as a joint effort between Chrysler, Ford, and General Motors to establish standard qualifications for parts. Important qualifications include AEC-Q100 for ICs, AEC-Q101 for discrete semiconductors, and AEC-Q200 for passive components. The qualification specifications include specific instructions on which tests shall be performed, as well as how to perform them. Parts with AEC qualifications are considered "suitable for use in harsh automotive environments without additional component-level qualification testing.".

Table 2.6: AEC-Q100 grades.

Grade	Temperature
0	−50°C to +150°C
1	−40°C to +125°C
2	−40°C to +105°C
3	−40°C to +85°C
4	−0°C to +70°C

Table 2.7: AEC-Q200 grades.

Grade	Temperature	Component type	Typical application
0	−50°C – 150°C	Flat chip ceramic resistors, X8R ceramic capacitors	All automotive
1	−40°C – 125°C	Capacitor networks, resistors, inductors, transformers, thermistors, resonators, crystals, ceramic and tantalum capacitors	Most underhood
2	−40°C – 105°C	Aluminium electrolytic capacitors	Passenger compartments hot spots
3	−40°C – 85°C	Film capacitors, ferrites, R/R-C networks and trimmer capacitors	Most passenger compartments
4	−0°C – 70°C		Non-automotive

2.5.6 Electrostatic discharge

Component stress covered in the previous sections heavily influences the lifetime of components, but it is only part of the reason for faults. The other reason is sudden, destructive events that may damage components instantly. The most common causes for this are mechanical shocks, for example, when a user drops a populated PCB on the ground or electrostatic discharge.

Electrostatic discharge is an event where a body (very commonly a human body) builds up a static electric charge, which subsequently discharges as the body comes into contact with a body holding a different electric potential. The maximum voltage of an electrostatic discharge may be several thousand volts, easily capable of damaging or destroying sensitive electronic components. This typically happens during the manufacture, handling, and testing of systems.

Low-impedance paths to electric ground, redirecting the harmful current away from sensitive components, is the standard method for mitigating ESD. Transient voltage suppression (TVS) diodes are commonly used for this purpose. The use of a TVS diode is shown in figure 2.8.

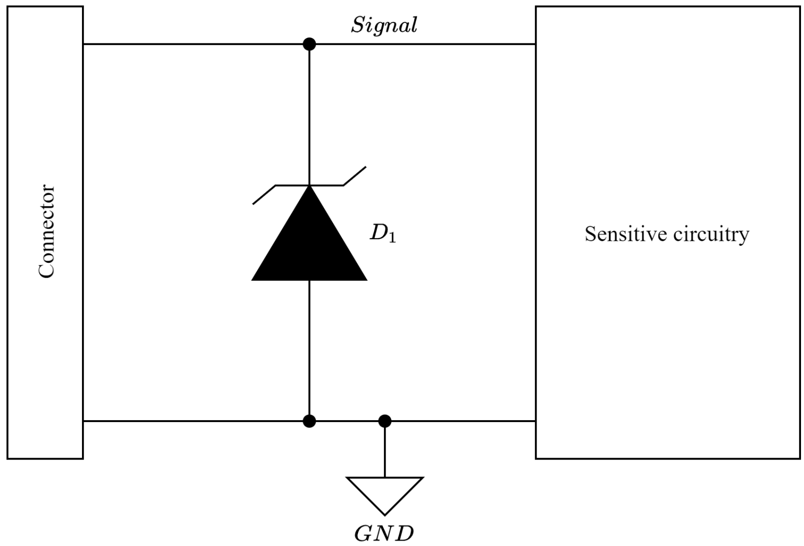


Figure 2.8: TVS diodes are typically Zener diodes capable of carriying large amounts of current (D_1 in this figure). Placing them close to connectors where discharges often happen ensures minimal damage to sensitive electronics.

Zener diodes create a low impedance path from the cathode to the anode (the blocking direction) whenever the reverse voltage reaches a certain threshold. Zener diodes with different reverse voltage thresholds are commonly available. Certain Zener diodes are marketed as TVS diodes and are specifically designed to dump large currents to ground.

2.5.7 Power supply protection

Protecting the power supplies against over-current/short circuits should be a priority [2, p. 151], as this is a very common error, and can make regulators overheat. Over-voltage protection is also desirable, ideally one that does not get permanently destroyed when subjected to over-voltage.

2.6 Maintainability engineering

Maintainability engineering is an area closely related to reliability engineering. While not a strict subsection, it is the other important discipline when considering availability/dependability. One way of looking at it is that reliability engineering deals with maximizing the lifetime of systems while maintainability deals with the recovery of failed systems. Important terms in maintainability engineering are *failure detection and localization*, *failure isolation* and *failure correction*.

The main point to take from maintainability engineering is to design systems in a way that simplifies recovery from a failure. A common technique for accomplishing this is to divide the system into easily replaceable parts, often called line-replaceable units (LRUs). It is also desirable to design the LRUs in a fashion that allows for repair.

2.6.1 Maintenance equipment at Revolve NTNU

At the Revolve NTNU headquarters in Trondheim, Norway, the team has access to soldering stations, microscopes, power supplies, multimeters, and oscilloscopes. Most of this equipment is brought to the competitions, and it is safe to assume that this equipment is available to the team members whenever the vehicle is operational. System placement in the vehicles determines the difficulty of retrieving them and maintaining them in the case of a failure. There are, for example, some systems located inside the battery pack (internally called the accumulator) of the vehicle, and access to these systems requires removal of the accumulator from the vehicle.

The systems that will go on the vehicle are produced at PCB assembly facilities owned by a sponsor, giving the team access to equipment which are not available during testing and competitions. For example, soldering is usually done in a reflow soldering oven, giving more robust and consistent solder joints than can easily be made by hand. This information is especially important to consider when choosing the packaging of components and their placement.

Chapter 3

Implementation

3.1 Requirements formation

As with any design process, creating a set of functional requirements from the problem specification should be the first step.

Before starting the development of the hardware and software, it is preferred to have a concise system specification to use as a platform. The following requirements is derived from the research done in chapter 2.

3.1.1 Resulting requirements

- Support power over both USB and directly from the carrier board.
- Provide proper supply protection for both the USB and carrier board supply.
- Allow for monitoring of the current drawn from the currently used 5V supply.
- Provide over-voltage protection for the 5V supplied by carrier board.
- Expose all available PWM, I^2C, SPI, UART and ADC interfaces available from the MCU.
- Be equipped with a 5V-to-3V3 voltage regulator.
- Expose 3V3 from the internal supply to the carrier board.
- Expose 3V and 1V5 precise reference voltages.
- Be equipped with 2 isolated CAN-FD transceivers capable of minimum 4 Mbit/s data transfer
- Expose the differential CAN-FD pairs on a dedicated connector as well as a means to disable on-board transceivers.
- Expose a dedicated pin on the CAN-FD connector for terminating the shielding on the CAN-FD cable.
- Expose a SWD header for programming and debugging the MCU.
- Be equipped with debug LEDs.
- Be equipped with a reset switch.
- Fit within he PCB enclosures usually used by Revolve NTNU.
- MEzzanine connectors must not build more than 8mm when stacked.
- Have prototype carrier board with pins allowing access to each pin on the breakout board.
- Have a test jig that can perform SWD debugging, reset and memory erase via spring loaded pins.

3.2 Architecture

Revolve NTNU has several years of experience designing embedded systems based on the ATSAME70N21B MCU. The MCU schematics and PCB layout developed as part of this project use Revolve NTNUs internal design documentation extensively.

Automotive embedded system implementation using System-on-Module [3] covers the hardware implementation of an advanced embedded electronics system at Revolve NTNU using a commercially available electronic processing module. The Enclustra Mercury ZX5 SoM used in the project, serves as an excellent example of a generic computing breakout board, albeit a more advanced and flexible processing platform.

Based on the requirements from 3.1, the breakout board partitioning shown in figure 3.1 was chosen for this project.

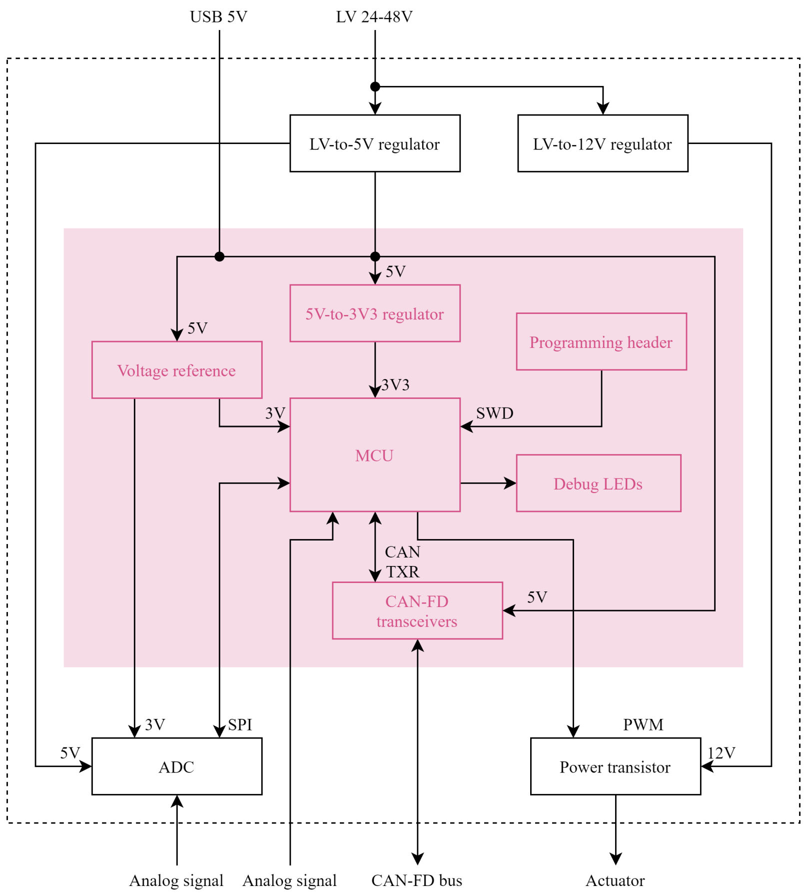


Figure 3.1: Breakout/carrier board partitioning. Colored area represents breakout board.

As per the requirements, a *prototype carrier board* and a *test jig* are designed around the breakout board.

3.2.1 Prototyping carrier board

While the breakout board is self-sufficient in the sense that it can be programmed and use its on-board peripherals without having a carrier board attached, most peripherals and GPIO pins on the MCU are only available on a carrier board. As testing the breakout board is an important part of the design process, a carrier board that allows for easy testing of all signals available through the mezzanine connectors should be designed. A decent interface for accessing the signals is 2.54mm headers, a physical interface that easily allows connecting to a *breadboard*, a solderless electronics prototyping platform that allows circuitry to be tested before PCBs are designed and produced. This is a technique which is currently not used in Revolve NTNU.

The carrier board designed will feature two 70-pin 2.54mm pitch headers, where each pin is directly connected to a corresponding pin on the mezzanine connectors, letting us inspect each signal line from the breakout board directly using a multimeter or oscilliscope.

3.2.2 Test Jig

Another interesting feature of having a common breakout board for multiple embedded systems is that the physical dimensions of the core circuitry will be the same, i.e. the points that should be probed when testing the system are shared. Because of this, the use of a *PCB test jig* is applicable.

PCB test jigs are PCBs that connect to a PCB in a certain fashion, either through one or more dedicated connectors, or with spring loaded pins that are forced against conductive test points on the PCB under test to make electrical contact. This is a technique extensively used in large scale production environments, but is less suited for the small scale production runs done by a FS team.

The test jig designed for this project is is able to perform several tasks that can simplify testing or would take up unnecessary space on the breakout board. It must be able to erase the flash memory of the MCU, sometimes necessary when the uploaded program code becomes corrupted. Programming the module using either SWD or JTAG should be possible. And at last have dedicated test points for measuring the voltage on the 3V3 rail and the VIN rail, which is convenient when the test jig is mounted and access to the underlying test pads is limited.

3.3 Microcontroller breakout board

3.3.1 MCU

Several parameters where taken into consideration when choosing the specific MCU for the breakout board. By opting for a 144-pin variant, more flexibility is given to the designer. Previous systems have used a 21-variant, meaning 2048kB of internal flash storage, this should be continued on the breakout board to ensure it has the enough internal storage for the program binaries.

Regarding the package, although a BGA package is preferable with regards to the physical size, they introduce a large penalty in the form of more advanced manufacturing techniques, increased difficulty in testing PCBs and finding faults. Because of this, a QFP package is chosen.

The breakout board is designed with the ATSAME70Q21B in mind, but it is the authors opinion that an ATSAMV71Q21B should be used for the production run. It is automotive rated and therefore more suited to Revolve NTNUs application. The V71 variant has a slightly higher unit cost, although this will extend the expected lifetime of the breakout board.

Oscillator

ATSAME70/V71 has an integrated oscillator allowing for CPU clock speeds as high as 300MHz, however CAN-FD and USB both require an external crystal to function properly. A 12MHz crystal oscillator was chosen and the *load capacitors* were chosen as per the specifications from the datasheet [1, p. 1876]. A through hole package was chosen to simplify soldering and desoldering.

Power filtering

Sophisticated ICs like MCUs are often sensitive to noise and transients from the power supply, making decoupling (or bypass) capacitors a must. Placing relatively small capacitors close to the IC power supply pins helps absorb and smooth out sudden changes on the voltage rails.

Most ICs have recommended values for decoupling capacitors, as well as the number and where to place them. This is also true for the ATSAME70/V71, and capacitors was added as per the datasheet recommendations [1, p. 1910].

Power stage

The power stage must meet several requirements. The 5V supply voltage from the carrier board must be protected against over-voltage. First and foremost, to protect the power supply against short circuits and overheating.

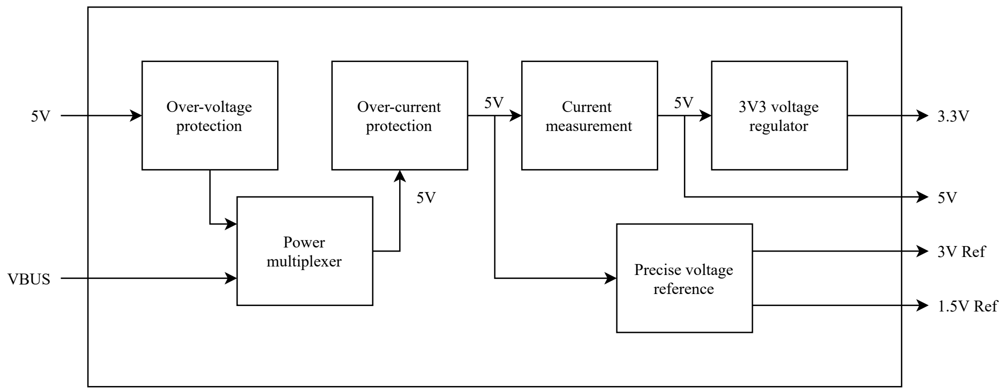


Figure 3.2: Breakout board power stage, includes precise voltage reference.

Over-voltage protection

To minimize the number of components used, Texas Instruments TS25200Q1 was chosen to provide over-voltage protection. The datasheet specifies that it clamps the output voltage to 5.4V up until the input exceeds 7.2V, when the output is disabled. This protects the power multiplexer and CAN-FD transceivers, both of which can handle up to 6V.

The IC can safely shut out an input voltage as high as 20V without failing, reducing the need for repair after applying too high of a voltage.

The Q1 variant of the IC is automotive rated, preferred for this application.

Calculating the maximum ambient temperature of the switch when operating under worst case conditions is also of interest.

$$\theta_A < 100°\text{C} - (7.2\text{V} - 5.4\text{V}) \cdot 500\text{mA} \cdot 66.5°\text{C}\,\text{W}^{-1} = 40.15°\text{C}$$

Power multiplexing

When a system can be powered from two individual power supplies, several challenges appear. If the supplies are directly connected, small variations in voltage may cause current to flow into a supply, possibly damaging it. This can be remedied using diodes, although the forward voltage drop makes this less attractive for low-voltage applications.

In this project a *power multiplexer* was chosen to deal with this issue. As the name indicates, a power multiplexer takes multiple supply inputs and outputs only one. Which supply is currently used can ordninarily be selected using simple configuration or automatically chosen depending on which supply is available.

The Texas Instruments TPS2115A-Q1 power multiplexer [4] was used. It was configured to prioritize the 5V supply from the mezzanine connector over the VBUS rail from USB.

Current limiting

A very common fault for electronic systems is short circuiting the power supply. This can cause permanent damage to circuits. Having an over-current protection effectively protects us from this kind of error, and should also prolong the lifetime of our components as there is a limit to the load they can be put under.

The TPS2115A-Q1 power multiplexer features an internal current limiter which can be configured using a resistor. The current limit is set to 500mA as this is the maximum current whihc can be delivered from a standard USB interface. This ensures no differences between the breakout board when operated from the mezzanine connector or a USB cable.

Current measurement

Data acquisition is an important aspect of the systems used at Revolve NTNU, and adding dedicated current measurement circuitry to the breakout board will serve as both a better way of detecting short circuits and keeping rack of power usage.

The current draw will be measured using the *shunt* method, where the voltage drop across a precise small value resistor is used to determine the amount of current drawn. The resistor is typically a special *current sense resistor* with a value of some tens of milliohms. The low resistor value ensures that the voltage drop over the current sense resistor does not affect the load, and since the resulting voltage drop will be quite small, an amplifier must be used. We will use the ADCs included in the MCU to perform the measurements.

The Texas Instruments INA190A4-Q1 [5] is used for amplifying the current sense resistor voltage drop, it is purpose built for current sense applications, and automotive rated. The A4-variant of the amplifier has a set gain A of 200, and the MCU ADCs operate in the range 0-3V. To have some margin, we set 600mA as a maximum current drawn.

$$600\text{mA} \cdot R_{sense} \cdot 200 = 3\text{V} \Rightarrow R_{sense} = 25\text{m}\Omega$$

We should also make sure the voltage drop over R_{sense} does not become too large.

$$500\text{mA} \cdot 25\text{mA} = 12.5\text{mV}$$

This is well within the allowed voltage range, the transceivers can operate down to 4.5V and the voltage reference can operate on as low as 3.02V.

Lastly, we look at the effect dissipated by the current sense resistor.

$$500\text{mA} \cdot 12.5\text{mV} = 6.25\text{mW}$$

Resistors should be derated with a factor of 0.6 in regards to power, so the resulting minimum power rating we get is

$$\frac{6.25\text{mW}}{0.6} = 10.4\text{mW}$$

Considering the results above, a Vishay Dale WSL1206R0250FEA[6] was chosen for this project. It is a 25mΩ current sense resistor, 1% error, 250mW max power and rated for automotive use.

The output of the current measurement amplifier will be fed into an ADC-enabled pin on the MCU. With a reference voltage V_{ref} of 3V and a ADC resolution of 12 bits, we get the following equation for calculating the power stage current I_{sense}.

$$I_{sense} = \frac{V_s \cdot V_{ref}}{2^{12}} \cdot \frac{1}{A \cdot R_{sense}} = V_s \cdot \frac{3\text{V}}{4096 \cdot 200 \cdot 0.025\Omega} = \frac{3\text{V}}{20480\Omega} V_s$$

V_s refers to the sampled value from the ADC.

3V3 voltage regulator

Bringing the 5V DC down to a stable 3.3V DC is necessary to properly power the MCU on the breakout. There are two main types of DC to DC regulators, *linear* and *switching* (often called Buck regulators). To ensure minimal ripple on the 3V3 rail, a linear regulator was chosen. The largest issue with a linear regulator is the low efficiency. Unlike in a switching regulator where energy is stored in a LC circuit, linear regulators dissipates extra energy as heat. On the other hand, linear regulators are simpler and requires less external components. It was therefore determined that a linear regulator could be sufficient *as long the thermals are properly managed.* We will use equation 2.1 to calculate the maximum ambient temperature. We can start by looking at how much power is dissipated as a worst case.

$$P_{max} = (5\text{V} - 3.3\text{V}) \cdot 500\text{mA} = 850\text{mW}$$

The thermal resistance R_{JA} can be found in the data sheet for our chosen linear regulator, LT1129, SOT-223 package [7, p. 11].

$$\theta_{A(max)} = 100°\text{C} - 850\text{mW} \cdot 59°\text{C}\,\text{W}^{-1} = 49.85°\text{C}$$

Derating was also taken into consideration when choosing a regulator. From table 2.5 we know that regulators should not supply more than 70% maximum current. Our maximum current is 500mA so the regulator must be able to supply

$$\frac{500\text{mA}}{0.7} = 714\text{mA}$$

The LTC1129 can supply 700mA which we deem close enough.

Separation

The electronic fuse, power multiplexer and voltage regulator are connected using ferrite beads, allowing for simple isolation of the individual parts in case of a failure. Ferrite beads are preferred over 0Ω (shunt) resistors, as they generally provide a lower resistance.

3.3.2 Voltage reference

A voltage reference provides a precise voltage commonly used with analog-to-digital converters. Having one on the breakout board simplifies layout for external ADCs and lets us supply the ADCs in the MCU. A Texas Instruments REF1930 [8] is used on the breakout board. It supplies both a reference voltage of 3.0V and 1.5V, which allows bidirectional current measurement.

3.3.3 CAN-FD transceivers

The breakout board shall be equipped with CAN-FD transceivers capable of transmitting data at 4Mb/s. Also, the concept for the CAN bus for the next season states that all communication between systems shall be galvanically isolated, meaning no current can pass between the systems. This concept eliminates *ground loops* generated from systems with slightly different ground potentials being electrically connected through multiple channels (communication and power lines) [9, p. 11].

Isolating the communication comes at a cost, however. Isolated transceivers must incorporate a transformer to ensure proper isolation, adding to the total size and price of the system. Also, powering both sides of the isolation barrier with voltages referenced to each other would nullify the isolation, it is necessary to use an isolated DC-to-DC converter for powering the isolated side. Isolated power supplies are also dependent on a transformer to achieve galvanic isolation, and use switching transistors to output the desired voltage, potentially generating noise on both power rails and communication lines. Proper filtering is required to deal with this side effect.

Analog Devices' ADM3055E was chosen as CAN-FD transceivers for this project. It incorporates an isolated DC-to-DC power supply, simplifying the design, at the cost of having two physically large transceivers on the PCB.

Disabling the CAN-FD transceivers is done by driving the IO-supply of the transceivers through a PMOS. The datasheet of the ADM3055E's specify that the CAN TXR pins goes to high-impedance if the IO-supply is driven low while the isolated supply is operational. The gate of the PMOS is pulled to groudn by a resistor, and the gate node is available through the mezzanine connector as *EXT_CAN*. Pulling this pin to 3V3 will disable the transceivers.

As the transceivers are directly connected to a connector on the breakout board, ESD protection should be present. Two Nexperia PESD2CANFD24V-T TVS diode pairs [10] were chosen for this purpose as it is automotive rated and specifically targeted to CAN-FD applications.

3.3.4 USB

Although USB is rarely used for anything other than power on the systems at Revolve NTNU, the protocol holds promise for use during development and testing.

Power over USB

The USB standard specifies a power rail available through the USB physical interface. It is called VBUS and should maintain a steady voltage of 5V, and be able to deliver a maximum of 500mA, for a total of 2.5W. In a common development situation, it is practical to power the module through a USB cable, making a dedicated power supply unnecessary. This does however put stringent requirements on the power supply of the module, as current under no circumstances can flow back out of the USB interface since this can damage the connected computer. Most commonly, this happens when multiple voltage sources are used to power the module at the same time, where small differences in voltages can cause unwanted currents.

A reasonable solution is equipping the module with a *power multiplexer* which automatically switches between available power supplies. If done correctly, this ensures that no currents can flow into any of the sources, and only one source is used at any one time.

Debugging over USB

The de-facto standard for logging debug information with MCUs is the universal asynchronous receiver-transmitter (UART) protocol. The physical part of the interface consists of just two conductors, TX (transmit) and RX (receive), along with being supported by almost all MCUs on the market, this makes it a very nice interface for debugging. This data must be printed to a terminal to useful, and serial communication interfaces have become much less common with personal computer over the last decades. The standard solution to this is using USB-to-UART bridge which translates the serial data sent over the UART lines to USB packages, as USB has become the standard interface for communication between PCs and peripherals.

As the module can be equipped with a fully featured USB interface, it should be possible to send serial data directly to a connected computer using only a cheap and commonly available USB cable. Revolve NTNU has previously not used the USB protocol to any extent, mostly in part to the high complexity of the protocol.

3.3.5 Mezzanine connector

Connecting a breakout board to the carrier board is done using one or more board-to-board connectors. As with the SoMs used as inspiration for this project, we utilize *mezzanine connectors* for this connection, letting us stack parallel boards. This allows for the most freedom in regards to routing the breakout and carrier board, and the high signal density needed to route almost all GPIO pins from the MCU to the carrier board.

A pair of Amphenol ICC MezzoStak [13] 70 pin connectors was chosen for this task. The5 are 0.5mm pith connectors, which while not the easiest to solder by hand, is absolutely doable with the help of a microscope. Each pin can handle 500mA of current, handle high speed signaling (at least 5Gb/s) and rated for 50 mating cycles. They are also hermaphroditic, meaning there is no difference between male and female connectors, simplifying inventory management at Revolve NTNU.

3.3.6 MCU peripherals

As mentioned in section 2.2, selecting the needed peripherals on a MCU is an important part of any design process. In this project, a list on peripherals not commonly used was first compiled. We already know of some of the important communication interfaces from figure 2.5. In addition to these, the pulse width modulation (PWM) peripheral, analog-to-digital converters, multimedia card interface and static memory controller will be prioritized. Table 3.1 shows the pins with dedicated use on the breakout board.

Table 3.1: MCU pins with dedicated uses. All except CAN-FD pins are not available through mezzanine connector. No important interface is made unusable by occupying the pins listed here.

Pin name	Function
PB2	CAN-FD TX 0
PB3	CAN-FD RX 0
PC12	CAN-FD RX 1
PC14	CAN-FD TX 1
PC15	Power supply current sensing
PC17	Yellow debug LED
PD13	Orange debug LED
PD14	Red debug LED
PD29	Green debug LED

3.3.7 Pinout

Figure 3.3 shows the chosen signals and rails for each pin on the two mezzanine connectors. The pinout is governed by the placement of the MCU on the PCB and signals are routed as short and straight as possible to the connector.

Connector A

VIN_5V	A1	A2	**VIN_5V**
VIN_5V	A3	A4	**VIN_5V**
GND	A5	A6	**GND**
REF_3V	A7	A8	**REF_1V5**
PE1	A9	A10	PE0
PE2	A11	A12	PD31
PE3	A13	A14	PD0
GND	A15	A16	PB13
PC0	A17	A18	PC25
PC27	A19	A20	**GND**
PC26	A21	A22	PD1
PC31	A23	A24	PD2
GND	A25	A26	PC24
PC30	A27	A28	PA29
PC29	A29	A30	PD3
CANFD1_RX	A31	A32	PC23
PC13	A33	A34	**GND**
VOUT_3V3	A35	A36	PD4
GND	A37	A38	PD5
PB1	A39	A40	PC22
PB0	A41	A42	PA15
PA20	A43	A44	**EXT_CAN**
PA19	A45	A46	PC7
GND	A47	A48	**VOUT_3V3**
PA18	A49	A50	**GND**
PA17	A51	A52	PD27
CANFD0_TX	A53	A54	PA23
PE4	A55	A56	PA16
GND	A57	A58	PA13
PE5	A59	A60	PC4
CANFD0_RX	A61	A62	PC3
PA21	A63	A64	**GND**
PD30	A65	A66	PC2
PA7	A67	A68	PC1
PA8	A69	A70	PA22

Connector B

PD8	B1	B2	PA28
PA6	B3	B4	PC18
PA30	B5	B6	PD9
PC19	B7	B8	**TRACESWO**
GND	B9	B10	PD15
PA31	B11	B12	PB4
PD7	B13	B14	**GND**
PC20	B15	B16	PA0
PD6	B17	B18	PD10
GND	B19	B20	PC16
PC21	B21	B22	PA1
PA14	B23	B24	PD11
PD25	B25	B26	**GND**
PD26	B27	B28	**CANFD1_TX**
GND	B29	B30	PC11
PC6	B31	B32	PA2
PD24	B33	B34	PD12
PA24	B35	B36	**GND**
PD23	B37	B38	PA3
VOUT_3V3	B39	B40	PC10
GND	B41	B42	**SWDCLK**
PC5	B43	B44	PC9
PA25	B45	B46	**VOUT_3V3**
PD22	B47	B48	**GND**
PA26	B49	B50	**RESET**
GND	B51	B52	PC8
PD21	B53	B54	**SDWIO**
PA11	B55	B56	PD16
PD20	B57	B58	**GND**
PA10	B59	B60	PA4
GND	B61	B62	PC28
PD19	B63	B64	PA9
PA12	B65	B66	PD17
PD18	B67	B68	PA5
PA27	B69	B70	PD28

Figure 3.3: Breakout board mezzanine connector pinouts. Left connector called 'A' and right called 'B'.

3.3.8 Breakout board size

It is desirable to keep the breakout board as small as possible. Due to the dual isolated CAN-FD transceivers, each with a footprint of 15.4mm by 10.30mm [12, p. 24], the final size of the breakout board is 50mm by 50mm.

Table 3.2: Revolve NTNU PCB sizes as of 2020.

System name	Width (mm)	Height (mm)
IR sensor hub	64	46
ACU		
Dashboard	110	78
DCU	74	50
SBS	150	50
Inverter Control		
AMS Master	142	60
CCC	66	75

Comparing the size of the breakout board with the sizes of current systems at Revolve NTNU in table 3.2 Shows that this is an acceptable size for all boards except IR sensor hub.

The module should have a relatively small footprint so that existing boards do not need to be resized to a large extent. Both the MCU and isolated CAN-FD transceivers have larger packages, and the size of the module was determined to be 50 by 50 mm.

3.3.9 Mechanical fastening

The retention force from the mezzanine connectors is given as 25 grams per contact pair. As the board is equipped with 70 pairs, this amounts to 1750 grams of force needed for un-mounting. Additionally, four mounting holes are added to the breakout board, allowing for even higher retention.

3.3.10 PCB layer stackup

The *stackup* of a PCB refers to the copper layers. This is a standard stackup for 4 layer PCBs, making it relatively cheap to produce at prototype production houses. 35µm corresponds to 1oz/ft^2, the standard copper thickness. The stackup displayed in table 3.3. The PCB has no special requirement for the core, so a standard glass fiber core (FR4) was chosen.

Table 3.3: Breakout board PCB layer stackup and copper weight.

Layer function	Copper weight
Signal	35µm
Ground	35µm
Power	35µm
Signal	35µm

3.3.11 PCB surface finish

PCBs employ copper to carry current, it does however corrode when exposed to atmospheric oxygen and is difficult to solder directly on to. It is therefore common to cover the PCB with kind of lacquer known as solder mask, which protects the copper. There is however still need to expose some of the copper, specifically to solder on components. For the exposed copper, a surface finish is generally used. The surface finish usually consists of a conductive material which covers the underlying copper.

Hot air leveled solder (HASL) is an economic alternative, covering the copper with tin. This is generally a good surface finish, although the hot air leveling process leaves an uneven surface, making it less ideal for fine-pitch SMD components.

Electroless nickel immersion gold (ENIG) protects the copper with a layer of nickel, protected by a layer of gold. Gold is particulary stable and resistant to corrosion, and the surface finish is additionally very flat and suitable for SMD. The ENIG finish does have a significantly higher cost compared to HASL.

This project employs ENIG on the breakout board and HASL on both the prototyping board and test jig. The breakout board is equipped with more smd components compared to the two other, and has multiple fine pitch components. As both the breakout board and the prototyping board are equipped with the 0.5mm pith mezzanine connectors, it will serve as a simple comparison on the solderability of each surface finish.

Chapter 4

Results

4.1 Assembly

All three PCBs was hand soldered using a fine-tip soldering iron and a microscope. With the exception of some footprints, no discernible errors to the design was found.

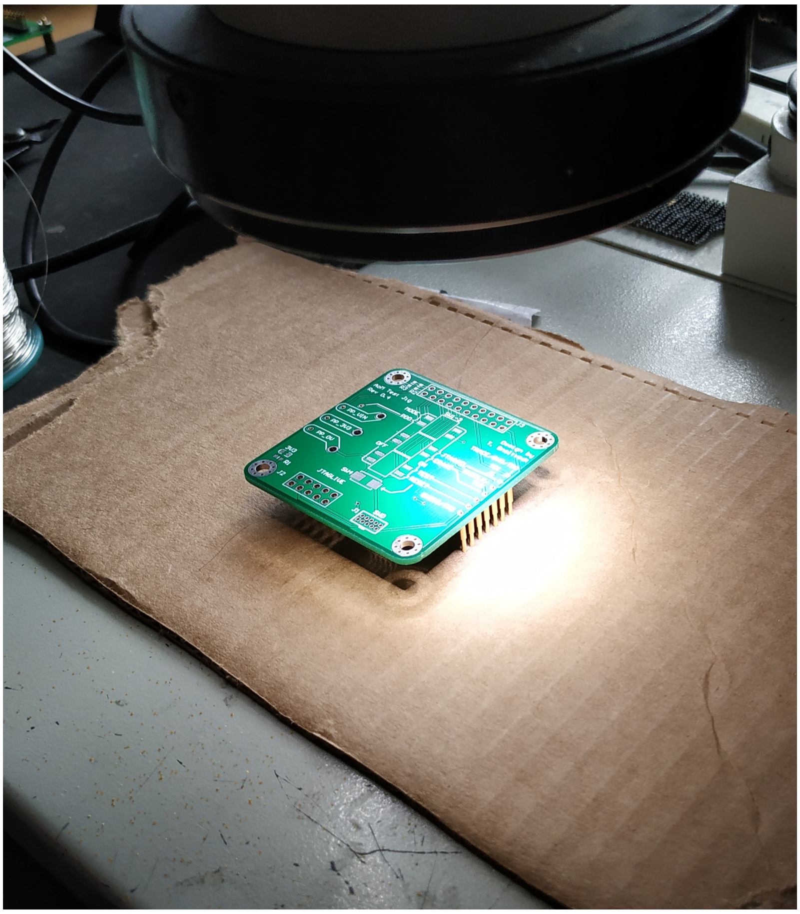


Figure 4.1: Assembly of test jig. Cardboard was used to hold pogo pins in place during soldering.

In regards to comparing the ENIG and HASL surface finishes, after soldering the 0.5mm pitch MezzoStak connectors to both the breakout board and the prototyping carrier board the author did not notice any difference in the ease of soldering between the two. There is however

Figure 4.1 shows part of the assembly process (soldering).

4.2 Testing

In regards to testing the module, this is done by creating and executing a test plan for verifying the functional requirements formed in 3.1. The test plan can be seen in appendix A.

4.2.1 Test equipment

A *NI myDAQ Student Data Acquisition Device* [14] was used for electric measurements. It is a generic electronic data capture device, capable of acting as a power supply, multimeter, 2-channel oscilloscope, logic analyzer and more.

CAN-FD was verified using a *Peak-System PCAN-USB FD* [15], a USB to CAN-FD dongle. Monitoring was done using the accompanying PCAN-View software.

An *Arduino Nano 33 IOT* MCU development board [16] was used as a UART-to-USB bridge. It is equipped with an ATSAM21 MCU, operating at 3.3V, making it compatible with the breakout board I/O voltage.

Lastly, an *Atmel-ICE debugger* [17] was used for programming and debugging of the breakout board.

Figure 4.2 shows the test setup.

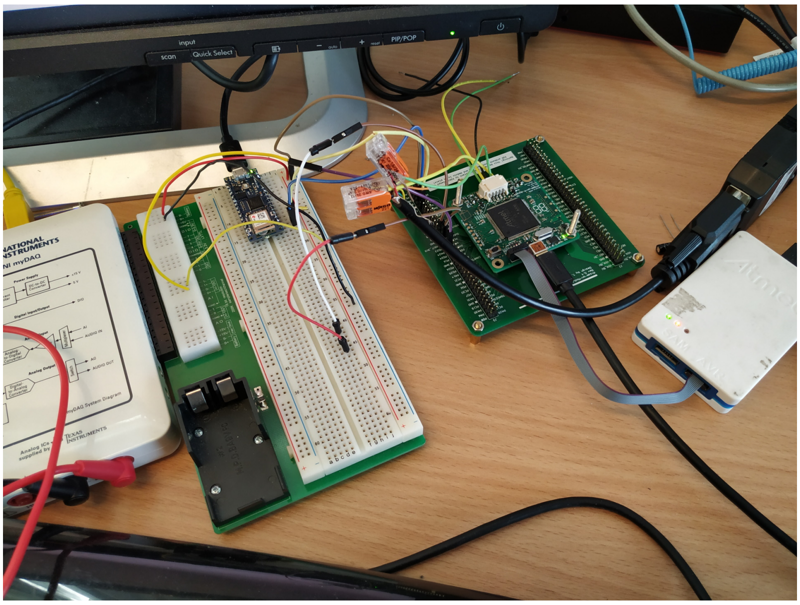


Figure 4.2: Test setup. From left: MyDAQ, Ardino Nano 33 IOT, breakout board on prototype carrier board, PCAN-USB FD, Atmel-ICE.

4.2.2 Test plan results

Power multiplexer

The multiplexer did not prioritize the 5V rail from the mezzanine connector over the USB VBUS as expected. This was due to an oversight, the datasheet of the TPS2115A-Q1 states that it prioritizes the input with the highest voltage.

This does not affect the operation of the breakout board in any meaningful way, although the test plan must be updated.

USB CDC

USB communication device class (CDC) is an USB device class that lets USB devices operate as a serial communications device. Although the author was unable to make it send data, the device appeared as a communication device on the computer used during testing. This was established by the USB CDC software example used, and indicates that the physical part of the USB protocol works as expected, it is the software that requires further work.

Instead of USB CDC, a UART interface was used for debug communication. This is not an issue for development, but making USB CDC working should be pursued by coming members.

Current sensing offset

While the current sense amplification circuit worked and the current can be read in real time, the current measured with the microcontroller was about 10mA lower than the current supplying the breakout board measured by the MyDAQ. While not a catastrophic error, it is still significant. Possible causes of this may be the layout of the sensing tracks to the current sense resistor pads [18].

4.3 Conclusion

A MCU breakout board has been designed and tested. Although the breakout board has yet to be tested in a race-car, the preliminary results indicate It is fully functional operating on the prototyping carrier board.

Reliability was the main design criteria, and while it is outside of the scope of this project to assess the lifetime of the breakout board, testing shows the system to be resilient to the most common errors, short circuits, and overvoltage.

Although the system should be more extensively tested in the coming seasons, preliminary testing indicates this is a system that could simplify and shorten the development cycle for Revolve NTNU in the coming seasons.

4.3.1 Further work

The implementation detailed in this project has room for improvements. The following list contains changes that should be made to the breakout board before a large production run.

- During soldering, some passive components were found to have irregular and hard-to-solder footprints. Transitioning to IPC-7351B low density land patterns [19] for all components should simplify assembly, repair and the mechanical strength of solder joints.
- Add ground fills to top and bottom planes, improving protections against ESD, simplifying layout and help reduce the temperature of especially the linear regulator.
- Lay out a guard ring around the oscillator [20], specifically for shielding the USB data lines.
- Replace overvoltage protection IC with a simple Zener diode. The current solution is hard to solder and provides protection against fault relatively easy to catch in earlier phases of development.

The current prototyping carrier board serves as a decent platform for the initial stages of hardware and software development, although a prototyping board more closely resembling a vehicle-ready carrier board would likely be just as easy to get started with. It could also serve as a template or inspiration for other carrier board designs.

Bibliography

[1] *SAM E70/S70/V70/V71 Family Data Sheet*. Microchip. 2019. URL: http://ww1.microchip.com/downloads/en/DeviceDoc/SAM-E70-S70-V70-V71-Family-Data-Sheet-DS60001527D.pdf.

[2] Alessandro Birolini. *Reliability engineering : theory and practice*. eng. 7th ed. Berlin ; Springer-Verlag, 2014. ISBN: 3-642-39535-X.

[3] Trym Sneltvedt. "Automotive embedded system implementation using System-on-Module". Report. Norwegian University of Science and Technology, 2019.

[4] *TPS2115A-Q1. Auto-Switching Power Multiplexer*. Texas Instruments. 2016. URL: https://www.ti.com/lit/ds/symlink/tps2115a-q1.pdf?ts=1593420053043&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTPS2115A-Q1.

[5] *INA190-Q1. Automotive, 40-V, High Precision, Low Bias Current, Low Power, Current Sense Amplifier*. Texas Instruments. 2019. URL: https://www.ti.com/lit/ds/symlink/ina190-q1.pdf?ts=1592761318394&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FINA190-Q1.

[6] *WSL. Power Metal Strip® Resistors, Low Value (Down to 0.0005 Ohm), Surface-Mount*. Vishay Dale. 2020. URL: https://www.vishay.com/docs/30100/wsl.pdf.

[7] *LT1123/LT1129-3.3/LT1129-5. Micropower Low Dropout Regulators with Shutdown*. Linear Technology. 1994. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/112935ff.pdf.

[8] *REF19xx. Low-Drift, Low-Power, Dual-Output, Vref and Vref/2 Voltage References*. Texas Instruments. 2017. URL: https://www.ti.com/lit/ds/symlink/ref1930.pdf?ts=1593423229392&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FREF1930.

[9] Analog Devices. *AN-1123. Controller Area Network (CAN) Implementation Guide*. 2017. URL: https://www.analog.com/media/en/technical-documentation/application-notes/AN-1123.pdf.

[10] *PESD2CANFD24V-T. ESD protection for In-vehicle networks*. Nexperia. 2020. URL: https://assets.nexperia.com/documents/data-sheet/PESD2CANFD24V-T.pdf.

[11] *LCBSBM drawings*. Essentra. 2012. URL: https://www.essentracomponents.com.sg/images-line/pdfs/LCBSBM.pdf.

[12] *ADM3055E/ADM3057E Rev. B. 5 kV rms/3 kV rms, Signal and Power Isolated, CAN Transceivers for CAN FD*. Analog Devices. 2019. URL: https://www.analog.com/media/en/technical-documentation/data-sheets/ADM3055E-3057E.pdf.

[13] *MEZZOSTAK® 0.5MM Mezzanine connectors*. Amphenol ICC. 2013. URL: https://cdn.amphenol-icc.com/media/wysiwyg/files/documentation/datasheet/boardwiretoboard/bwb_mezzostak0.5mm_mezzanine.pdf.

[14] *Device Specifications NI myDAQ*. NI. 2019. URL: http://www.ni.com/pdf/manuals/373061g.pdf.

[15] *PCAn-USB FD User Manual*. PEAK-System Technik Ghmb. 2019. URL: https://www.peak-system.com/produktcd/Pdf/English/PCAN-USB-FD_UserMan_eng.pdf.

[16] Arduino. *Arduino Nano 33 IOT Store Page*. 2020. URL: https://store.arduino.cc/arduino-nano-33-iot.

[17] *Atmel-ICE User Guide*. Atmel Corporation. 2016. URL: http://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-ICE_UserGuide.pdf.

[18] Marcus O'Sullivan. *Optimize High-Current Sensing Accuracy by Improving Pad Layout of Low-Value Shunt Resistors*. 2012. URL: https://www.analog.com/media/en/analog-dialogue/volume-46/number-2/articles/optimize-high-current-sensing-accuracy.pdf.

[19] Tom Hausherr. *PCB Design Perfection Starts in the CAD Library – Part 12*. 2011. URL: https://blogs.mentor.com/tom-hausherr/blog/2011/01/28/pcb-design-perfection-starts-in-the-cad-library-part-12/.

[20] STMicroelectronics. *AN2867. Oscillator design guide for STM8AF/AL/S, STM32 MCUs and MPUs*. 2020. URL: https://www.st.com/resource/en/application_note/cd00221665-oscillator-design-guide-for-stm8af-al-s-stm32-mcus-and-mpus-stmicroelectronics.pdf.

Appendix A

Test plan

ATSAM-on-Module Rev 0.4 Test Plan

Standard equipment: Multimeter, DC power supply, UART-to-USB converter, mini-USB cable, Atmel-ICE (or comparable SWD programmer/debugger)

Test order	Target	Required components	How to test	Criteria for test passing	Extra equipment	Test status	Comment	Importance
1	Over-voltage protection	U1, R1, R4	Apply 5V, 7V and 9V to VIN, measure voltage on OUT pin of e-fuse	5V in gives 5V out. 7V in gives 5.4V out (clamped). 9V gives 0V out (cutoff)		Passed		Must
2	Power multiplexer	L9, C1, C2, U2, R3, R2, L10, J4, R6, C6, D1	Solder a 100 ohm load to 5V rail. Connect a USB with inline currrent measurement. Connect 5V to VIN with inline current measurement.	Module continues to operate when sources are plugged in and unplugged. Current from USB drops to 0 when VIN is connected.		Failed	The multiplexer manages to switch between the supplies, but the supply with the highest voltage has precedence. Not a real issue, but technically a fail. Test plan should be updated to reflect this.	Must
3	Linear dropout regulator	C3, U3, C4, PWR, R5	Power module over USB, measure 3V3 measuring point.	Measure 3.3V +/- 10% on test point.		Passed		Must
4	Over-current protection		Connect a 5 ohm power-resistor (minimum 2W) to 3V3 an 0V rail using the protoboard. Measure current running into module. Power the module.	Module shuts down/will not start (PWR LED not emitting light). No or very little current running into module.		Passed		Must
5	Short-circuit protection		Short 3V3 and 0V rail. Power module.	Module shuts down/will not start (PWR LED not emitting light).		Passed	An extension of the over-current protection.	Must
6	Debug LEDs and SWD header	C7, J5, D2, R7, R8, R9, R10, U6, X1, C8-C28, R12, L1-L4, R13 , LED_R, LED_O, LED_Y, LED_G, R15-R18	Connect Atmel ICE to SWD header using the AVR output and flash the blinker example code.	Debug LEDs starts blinking at 0.5 Hz		Passed		Must
7	Reset switch	RST, R11, C45	Power module, flash blink firmware. Press reset button.	LEDs stop blinking with the desired freqency, module restarts.		Passed		Must
8	USB CDC		Connect UART-to-USB bridge to USART TXD0, RXD0 and computer. Connect USB cable from computer to module. Run ASF USB CDC example firmware.	Messages sent to one COM port is received on the other.		Failed	Was unable to get example USB firmware to work, but the breakout board showed up as a virtual COM port in Windows. It seems USB works, but the software must be tweaked.	Should
9	UART on protoboard		Connect UART-to-USB bridge to PA9,PA10 and computer. Power module. Flash UART test firmware.	Receive test firmware printing.		Passed	This test both indicates that communication through the protoboard is possible and UART acts as a backup debug interface in case USB CDC is not working.	Must
10	CAN-FD transceivers	Q1, R14, C29-C44, L5-L8, U7, U8,	Connect PCAN to module, power module with USB, upload CAN-FD test firmware.	Can transmit and receive frames to both interfaces	PCAN-USB FD	Passed		Must
11	Disable CAN pin		Run CAN-FD test firmware when EXT_CAN is tied to 3V3.	Transceivers unresponsive.	PCAN-USB FD	Passed	Did not perform the test with external transceivers, howerer the CAN TXR-pins was inspected with an oscilloscope and the TXR signal was present. Testing with external CAN-transceivers should be made part of test plan.	Must
12	Current measurement	U4, C46	Measure current drawn by module using a multimeter or similar. Run test firmware and read measured current over CDC/UART. Add/remove 100 ohm resistor between 3V3 and 0V while module is measuring current.	See a jump of about 33mA when resistor is connected.		Passed	Somewhat sporadic measurements, shoud probably be an average of multiple samples. Noticeable offset of about 10mA from the current measured with multimeter.	Must
13	PWM on protoboard	J1, J2	Power module. Upload PWM example. Monitor PWM pin with oscilloscope.	A PWM waveform is present on the pin.	Oscilloscope	Passed		Must
14	Voltage reference	C5, U5	Power module. Measure reference voltages on exposed vias using a decent multimeter.	Reference voltages measure 3.00V and 1.50V		Passed	Should have marked the relevant vias. Consider adding proper test points for future versions.	Must

Figure A.1: Breakout board test plan.

Appendix B

Technical drawings

B.1 Module

B.1.1 Schematics

Revolve NTNU ATSAM-on-Module

This is the schematics for the Revolve NTNU ATSAM-on-Module (AoM). Main design goals:
1. Increase development speed of embedded electronics systems using the Microchip ATSAME70 platform
2. Increase reliability and maintanability of the embedded electronics systems using a ATSAME70 MCU
3. Increase the amount of reuse in the Revolve NTNU organization

Key features

- 144 pin ATSAM MCU
- Fully functional module without a carrierboard
- 103 GPIO lines available through two 70 pin mezzanine connectors
- Robust internal 3V3 linear dropout regulator with overcurrent protection
- Can be supplied with both 5V through mezzanine connectors and USB
- Two integrated isolated CAN-FD transcievers with dedicated connector
- Pin for disabling internal transceivers if there is need for external ones
- Full speed USB interface
- SWD programming header
- Reset switch
- 4 general purpose LEDs
- Integrated current measurement connected to ADC pin on MCU
- JTAG boundry testing available through test points

NOTE: This schematic document does NOT use hierarchical sheet structure like Revolve NTNU strongly recommends. This was decided against because of the massive amount of signals without dedicated roles, Which in the designers opinion does not match well with eiither harnesses or busses. I do not suggest using this structure for your own schematics, stick to the hierarchical system normally used by Revolve NTNU.

Rev 0.4

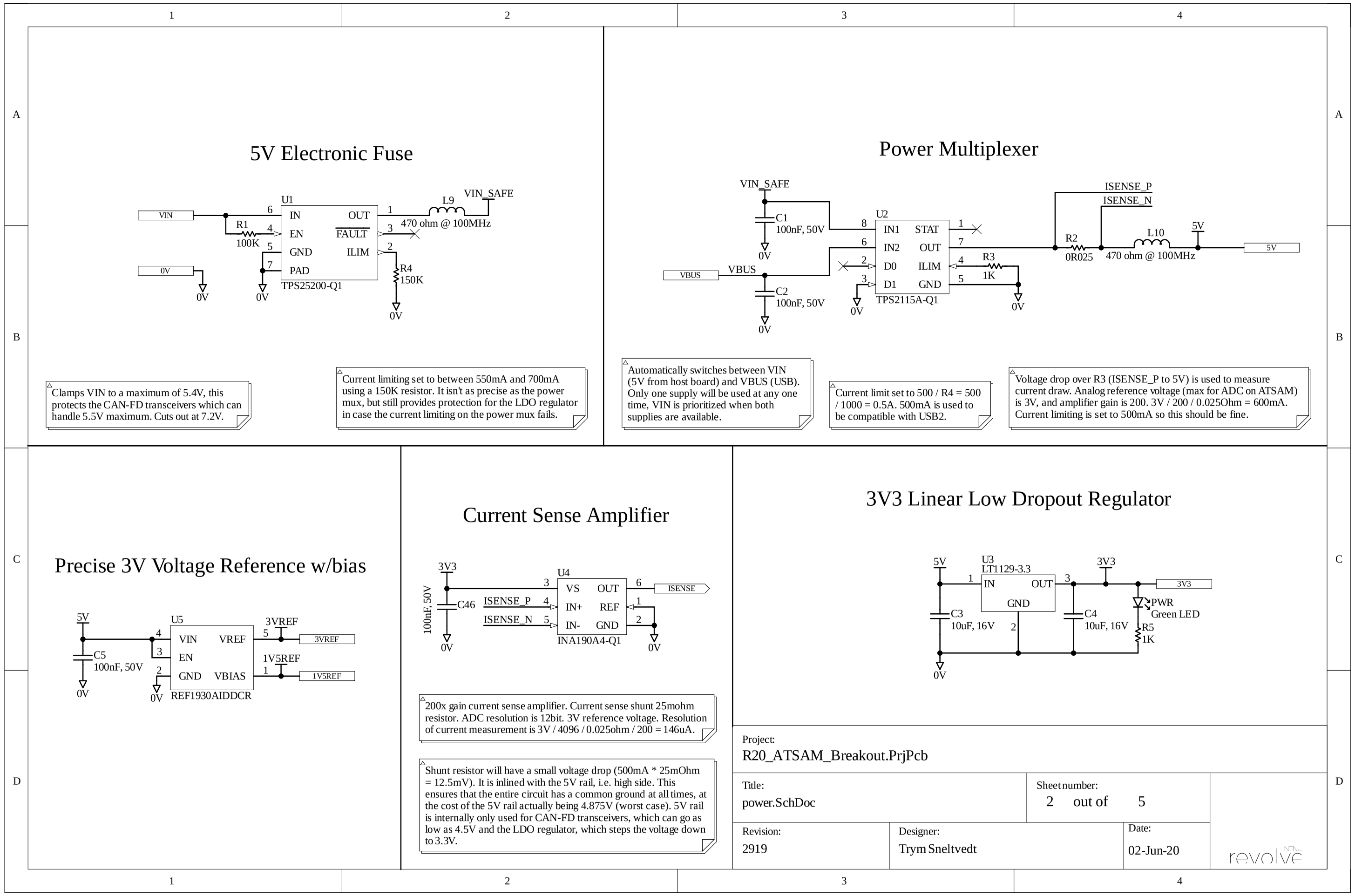
Changelog

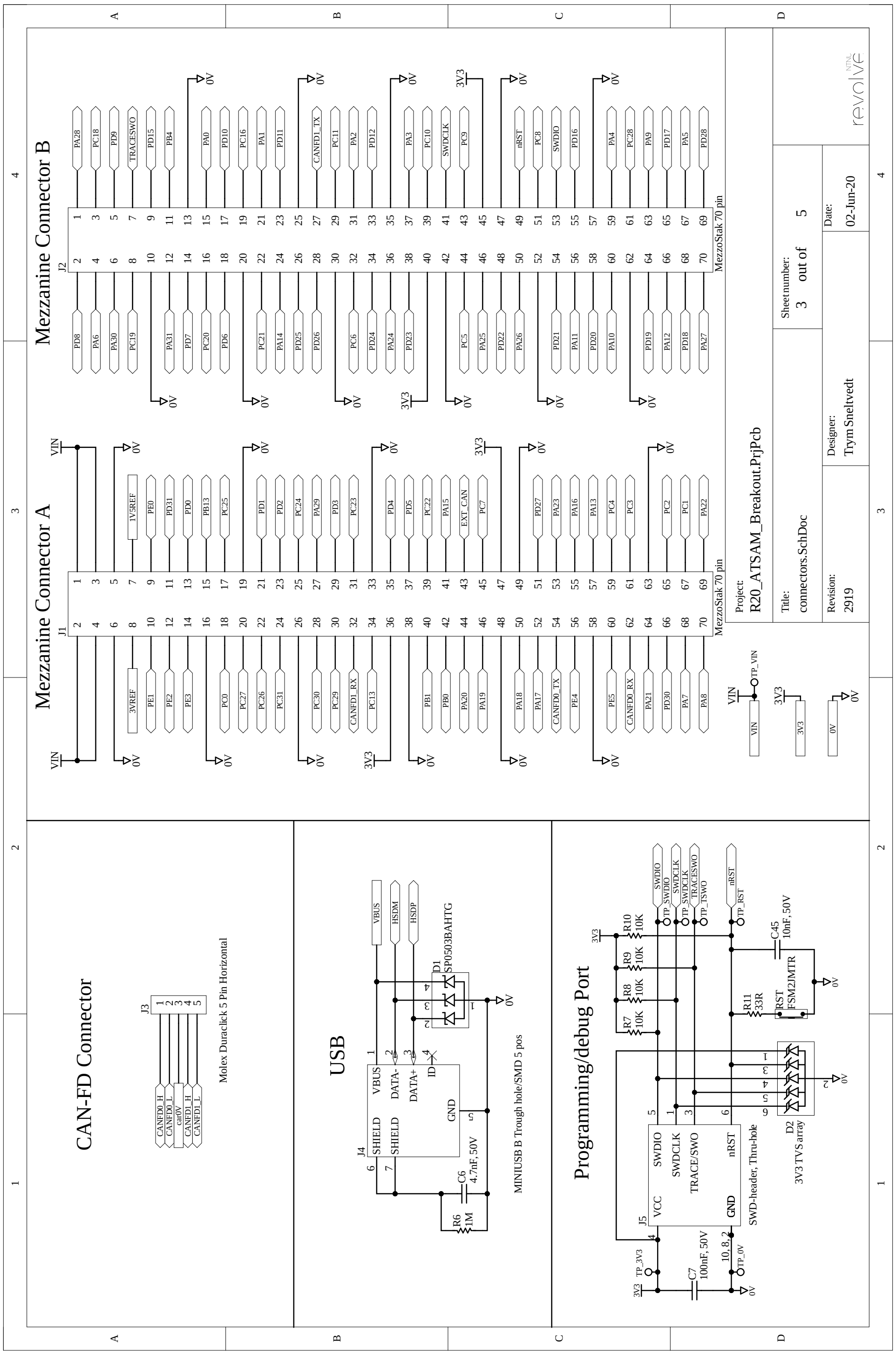
Rev 0.4
- Added ferrite beads between power ICs to simplify debugging
- Added TRACESWO to Mezzostak, it was missing
- Switch to through-hole crystal, capactitors are also changed
- Add capacitor to reset line
- Switch programming singal pull-ups from 100K to 10K
- Add testpads for 3V3 and 0V
- Add netlabels to CANFD H and L
- Switch LED G and Y, and R and O for simpler routing
- Add bypass capacitor to current sense amp
- Rename power LED to PWR
- Update key features

Rev 0.3
- Switched voltage reference to REF1930, includes a bias output
- Switched 12MHz crystal and capacitors to one that follows the datasheet requirements
- Fixed erroneous capacitor values for ADM3055
- Moved debug LEDs to peripheral sheet and reduced the count from 7 to 4
- Moved MCU decoupling capacitors to atsam sheet
- Add missing MCU decoupling capacitor
- Switch from sourcing to sinking LEDs
- Switch to 70 pin connectors
- Add voltage references to connectors
- Add way more ground pins to the connectors
- Add 3V3 power LED
- Minor aesthetic changes
- Switched back to 5 pin DuraClick, grounding is needed
- Added test points to test/debug/programming signals
- Added more notes to power sheet
- Changed VREFP filter to adhere to SAMV71-XPLD reference design
- Update key features

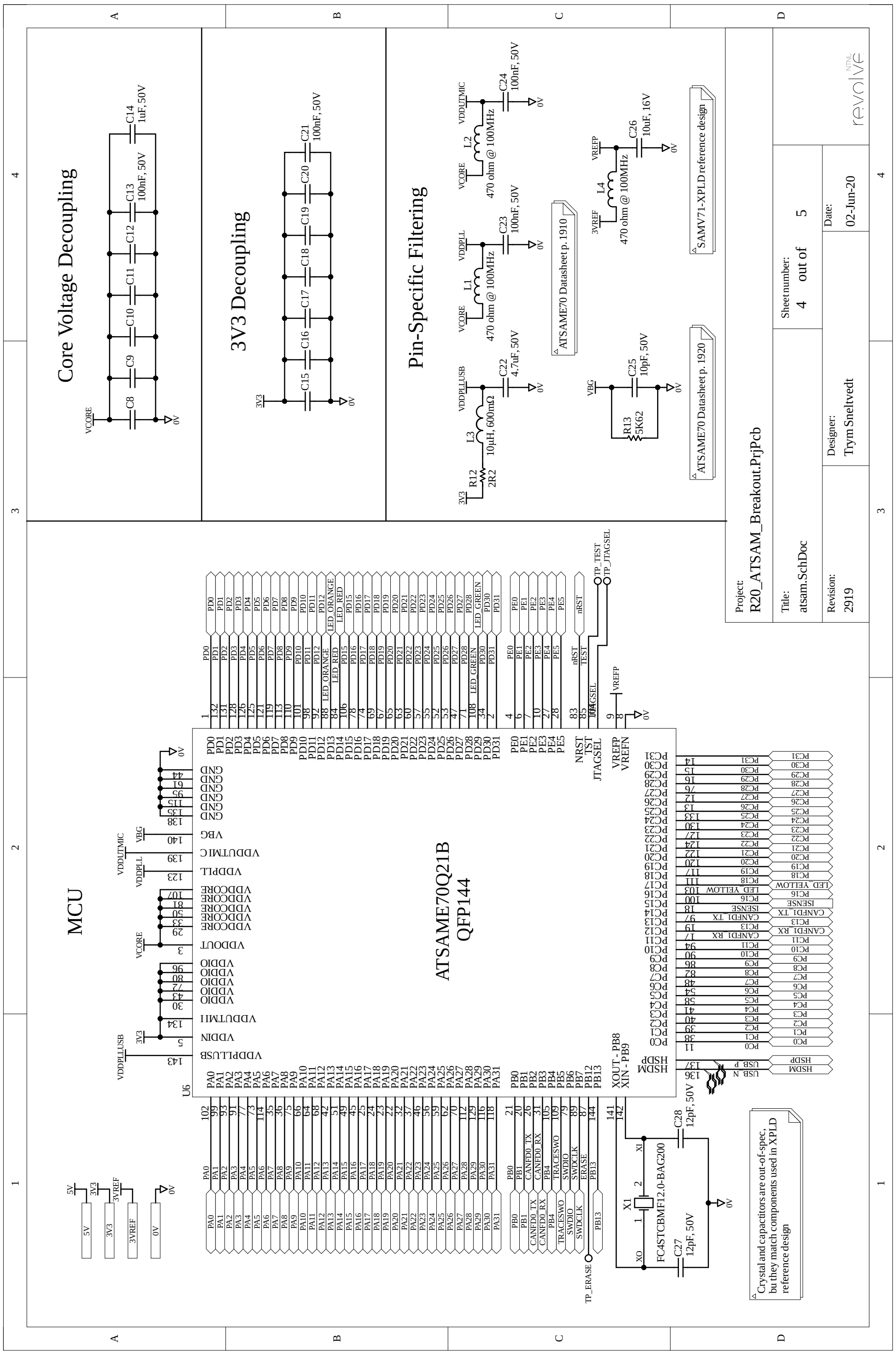
Rev 0.2
- Moved CAN TVS' to peripherals sheet and grounded them to car0V
- Switched from 5 pin DuraClick to 4 pin, grounding not needed
- CAN TXR now on mezzanine connectors
- Changed pinout of mezzanine connectors
- Added 3 LEDs to use pins there is no space for in mezzanine connectors
- Updated key features list

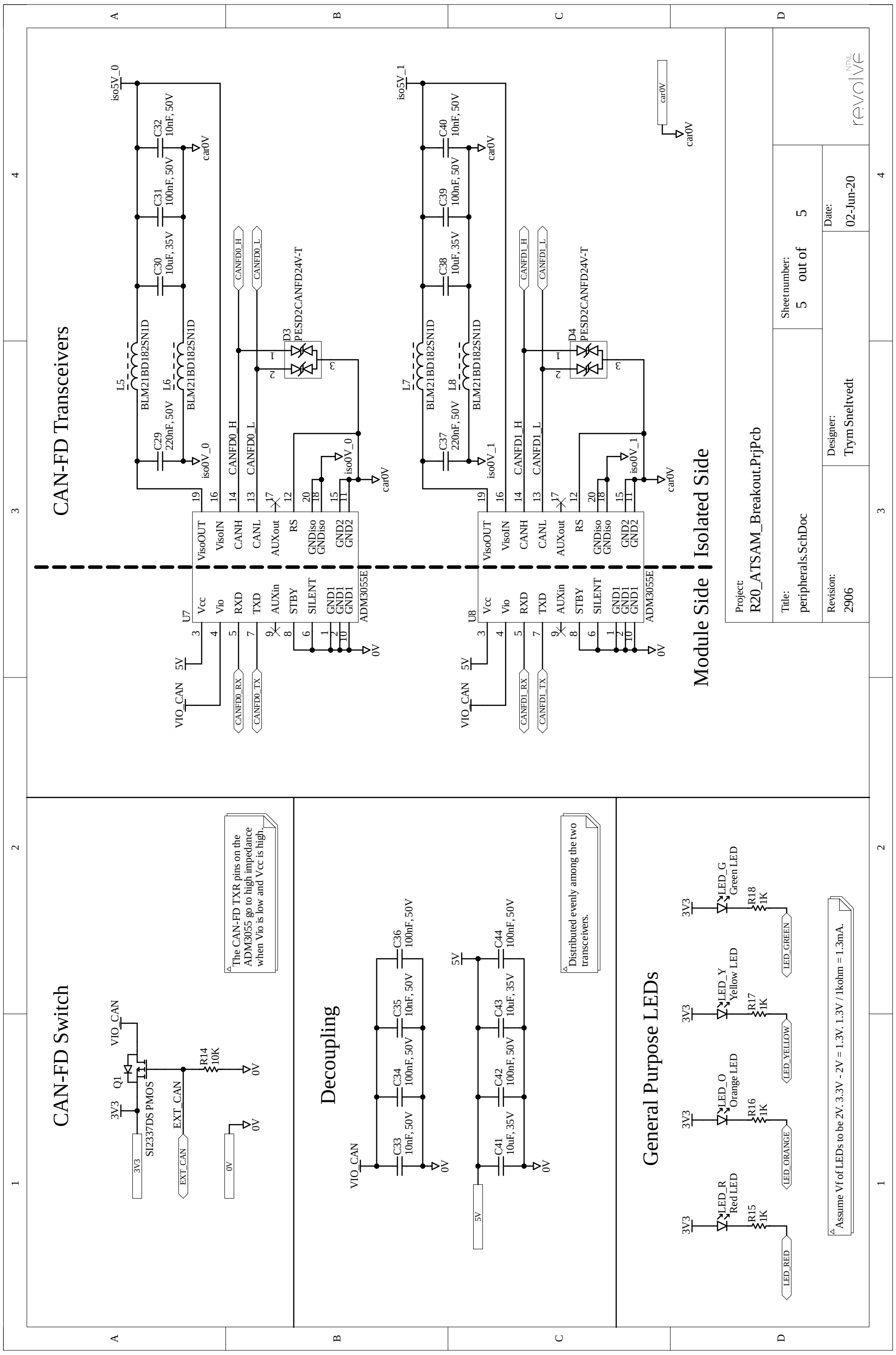
Project: R20_ATSAM_Breakout.PrjPcb			
Title: overview.SchDoc		Sheet number: 1 out of 5	
Revision: 2906	Designer: Trym Sneltvedt	Date: 02-Jun-20	revolve NTNU


5V Electronic Fuse
VIN
0V
R1
100K
U1
IN
EN
GND
PAD
OUT
FAULT
ILIM
TPS25200-Q1
L9
470 ohm @ 100MHz
VIN_SAFE
R4
150K
Clamps VIN to a maximum of 5.4V, this protects the CAN-FD transceivers which can handle 5.5V maximum. Cuts out at 7.2V.
Current limiting set to between 550mA and 700mA using a 150K resistor. It isn't as precise as the power mux, but still provides protection for the LDO regulator in case the current limiting on the power mux fails.
Power Multiplexer
VIN_SAFE
C1
100nF, 50V
VBUS
C2
100nF, 50V
U2
IN1
IN2
D0
D1
STAT
OUT
ILIM
GND
TPS2115A-Q1
R3
1K
ISENSE_P
ISENSE_N
R2
0R025
L10
470 ohm @ 100MHz
5V
Automatically switches between VIN (5V from host board) and VBUS (USB). Only one supply will be used at any one time, VIN is prioritized when both supplies are available.
Current limit set to 500 / R4 = 500 / 1000 = 0.5A. 500mA is used to be compatible with USB2.
Voltage drop over R3 (ISENSE_P to 5V) is used to measure current draw. Analog reference voltage (max for ADC on ATSAM) is 3V, and amplifier gain is 200. 3V / 200 / 0.025Ohm = 600mA. Current limiting is set to 500mA so this should be fine.
Precise 3V Voltage Reference w/bias
5V
C5
100nF, 50V
U5
VIN
EN
GND
VREF
VBIAS
REF1930AIDDCR
3VREF
1V5REF
Current Sense Amplifier
3V3
C46
100nF, 50V
ISENSE_P
ISENSE_N
U4
VS
IN+
IN-
OUT
REF
GND
INA190A4-Q1
ISENSE
200x gain current sense amplifier. Current sense shunt 25mohm resistor. ADC resolution is 12bit. 3V reference voltage. Resolution of current measurement is 3V / 4096 / 0.025ohm / 200 = 146uA.
Shunt resistor will have a small voltage drop (500mA * 25mOhm = 12.5mV). It is inlined with the 5V rail, i.e. high side. This ensures that the entire circuit has a common ground at all times, at the cost of the 5V rail actually being 4.875V (worst case). 5V rail is internally only used for CAN-FD transceivers, which can go as low as 4.5V and the LDO regulator, which steps the voltage down to 3.3V.
3V3 Linear Low Dropout Regulator
U3
LT1129-3.3
IN
OUT
GND
C3
10uF, 16V
C4
10uF, 16V
PWR
Green LED
R5
1K
3V3
0V
Project:
R20_ATSAM_Breakout.PrjPcb
Title:
power.SchDoc
Sheet number:
2 out of 5
Revision:
2919
Designer:
Trym Sneltvedt
Date:
02-Jun-20
revolve



Mezzanine Connector A
Mezzanine Connector B
CAN-FD Connector
USB
Programming/debug Port
Molex Duraclick 5 Pin Horizontal
MINIUSB B Trough hole/SMD 5 pos
SWD-header, Thru-hole
3V3 TVS array
MezzoStak 70 pin
Project:
R20_ATSAM_Breakout.PrjPcb
Title:
connectors.SchDoc
Sheet number:
3 out of 5
Revision:
2919
Designer:
Trym Sneltvedt
Date:
02-Jun-20


Core Voltage Decoupling
3V3 Decoupling
Pin-Specific Filtering
MCU
ATSAME70Q21B
QFP144
ATSAME70 Datasheet p. 1910
ATSAME70 Datasheet p. 1920
SAMV71-XPLD reference design
Crystal and capacitors are out-of-spec, bu they match components used in XPLD reference design
FC4STCBMF12.0-BAG200
Project:
R20_ATSAM_Breakout.PrjPcb
Title:
atsam.SchDoc
Sheet number:
4 out of 5
Revision:
2919
Designer:
Trym Sneltvedt
Date:
02-Jun-20
revolve


CAN-FD Transceivers
CAN-FD Switch
Decoupling
General Purpose LEDs
Module Side
Isolated Side
U7
U8
ADM3055E
VisoOUT
VisoIN
CANH
CANL
AUXout
RS
GNDiso
GND2
Vcc
Vio
RXD
TXD
AUXin
STBY
SILENT
GND1
iso5V_0
iso5V_1
iso0V_0
iso0V_1
car0V
VIO_CAN
5V
0V
3V3
CANFD0_H
CANFD0_L
CANFD1_H
CANFD1_L
CANFD0_RX
CANFD0_TX
CANFD1_RX
CANFD1_TX
L5
L6
L7
L8
BLM21BD182SN1D
D3
D4
PESD2CANFD24V-T
C29
220nF, 50V
C30
10uF, 35V
C31
100nF, 50V
C32
10nF, 50V
C37
220nF, 50V
C38
10uF, 35V
C39
100nF, 50V
C40
10nF, 50V
Q1
SI2337DS PMOS
EXT_CAN
R14
10K
The CAN-FD TXR pins on the ADM3055 go to high impedance when Vio is low and Vcc is high.
C33
10nF, 50V
C34
100nF, 50V
C35
10nF, 50V
C36
100nF, 50V
C41
10uF, 35V
C42
100nF, 50V
C43
10uF, 35V
C44
100nF, 50V
Distributed evenly among the two transceivers.
LED_R
Red LED
R15
1K
LED_RED
LED_O
Orange LED
R16
1K
LED_ORANGE
LED_Y
Yellow LED
R17
1K
LED_YELLOW
LED_G
Green LED
R18
1K
LED_GREEN
Assume Vf of LEDs to be 2V. 3.3V - 2V = 1.3V. 1.3V / 1kohm = 1.3mA.
Project:
R20_ATSAM_Breakout.PrjPcb
Title:
peripherals.SchDoc
Sheet number:
5 out of 5
Revision:
2906
Designer:
Trym Sneltvedt
Date:
02-Jun-20
revolve

B.1.2 Layout

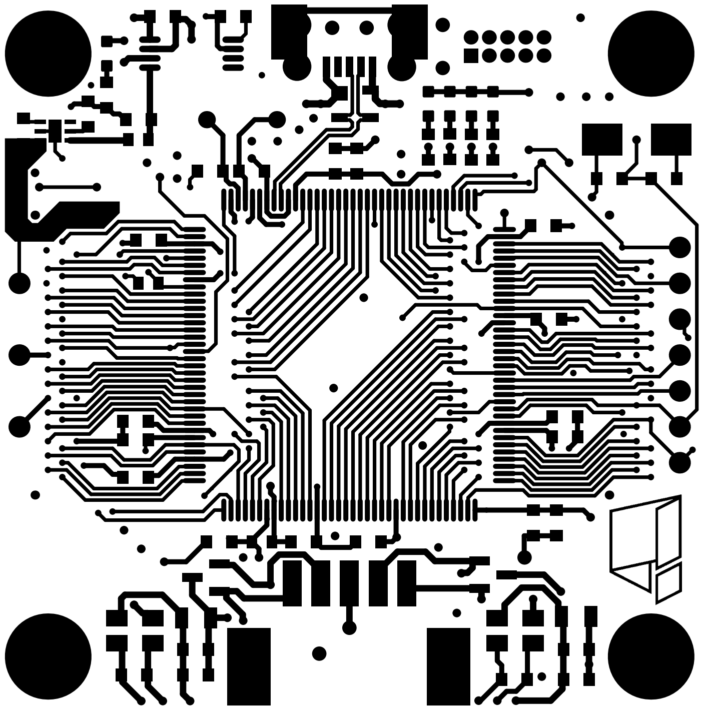


Figure B.1: Breakout board top layer.

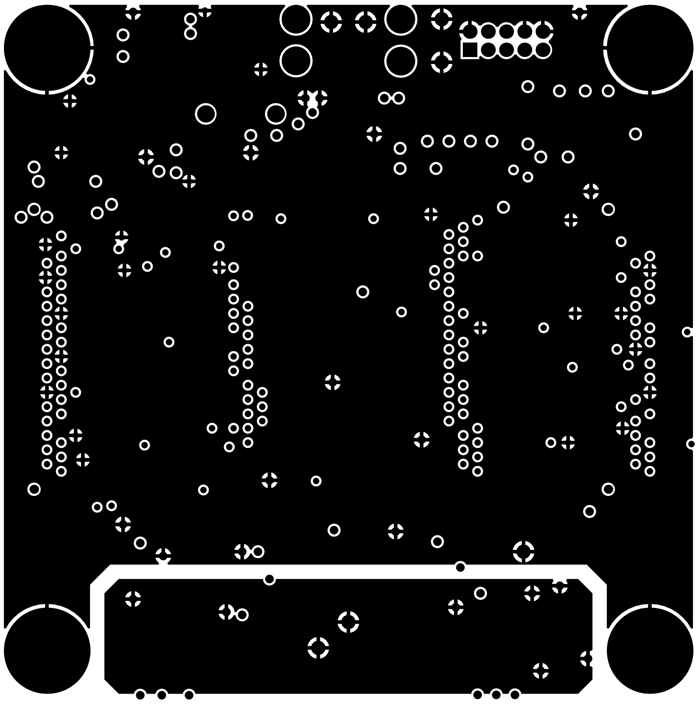


Figure B.2: Breakout board ground layer.

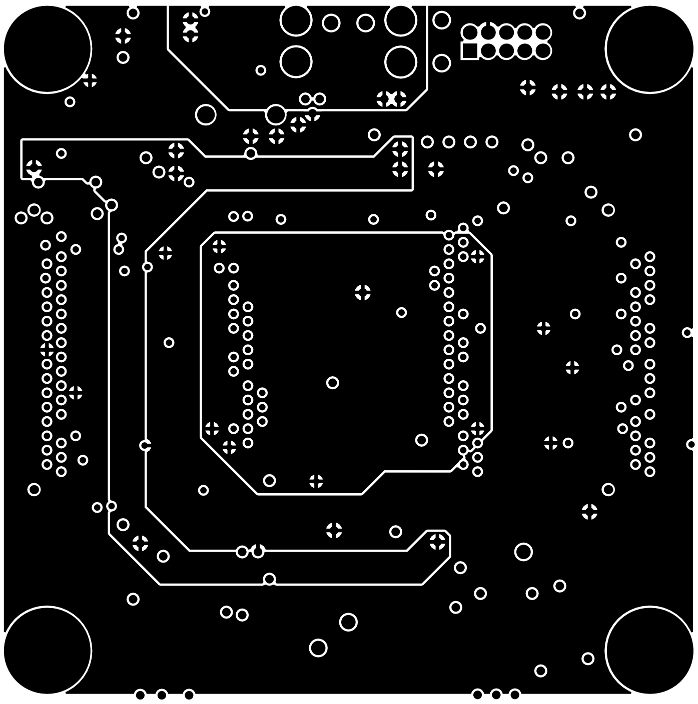


Figure B.3: Breakout board power layer.

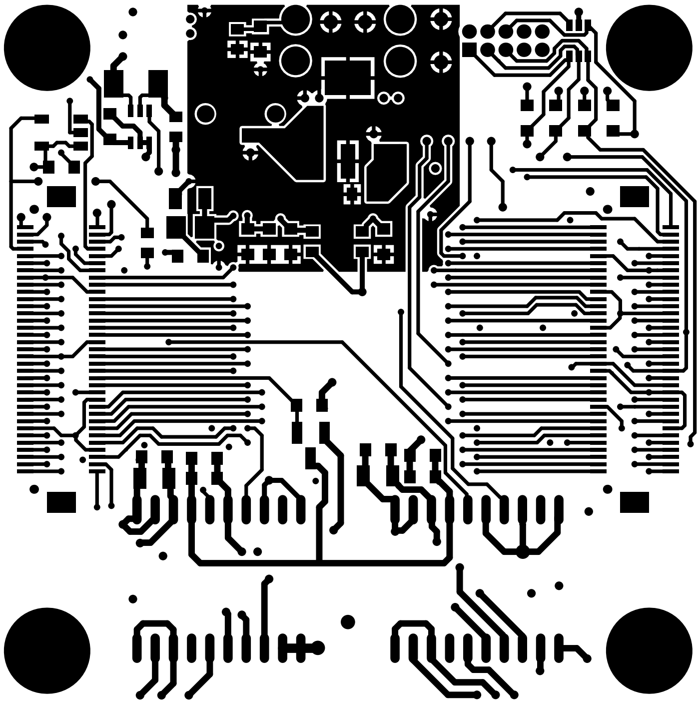
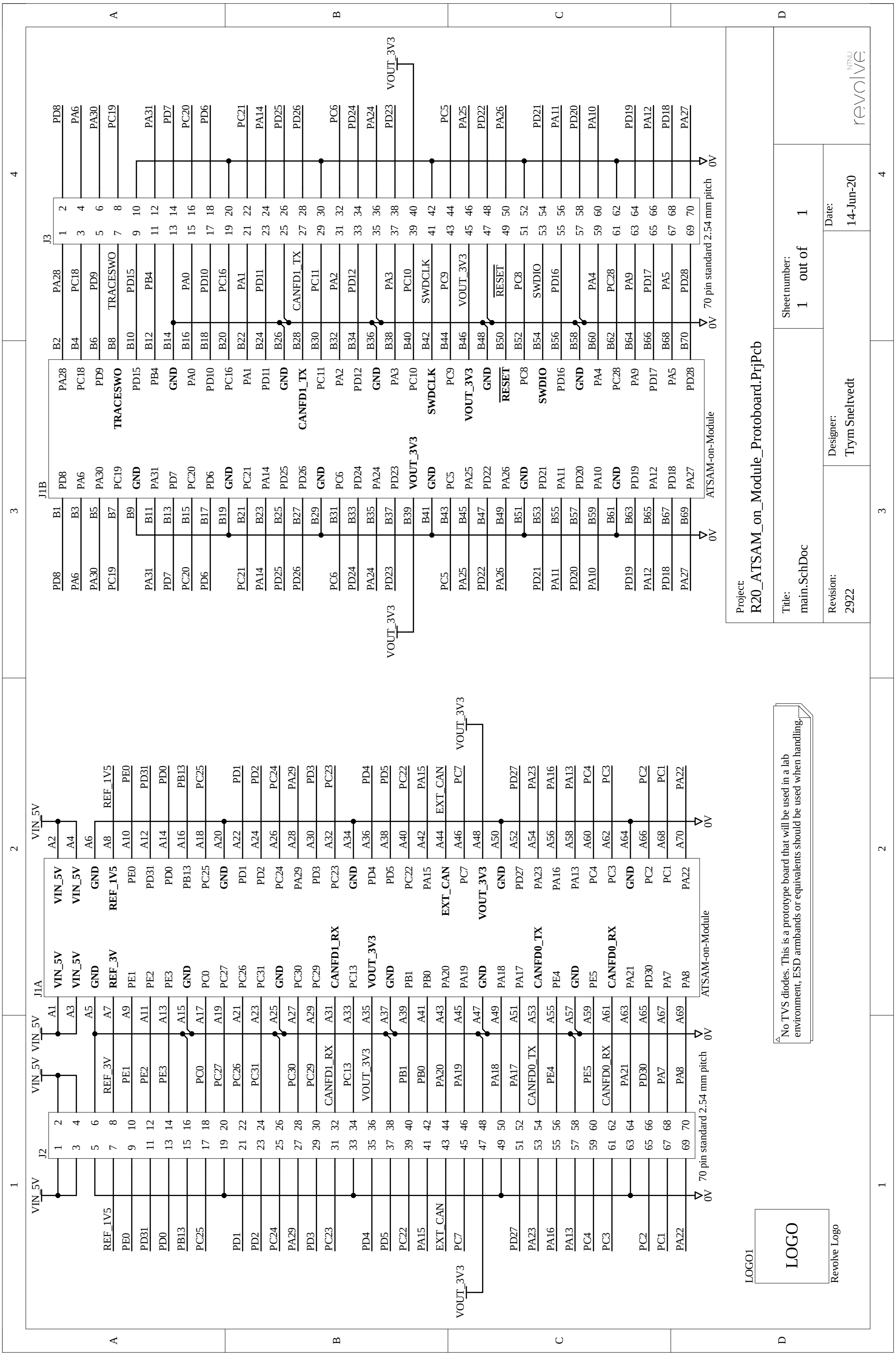


Figure B.4: Breakout board bottom layer.

B.2 Prototype carrier board

B.2.1 Schematics


Project:
R20_ATSAM_on_Module_Protoboard.PrjPcb
Title:
main.SchDoc
Sheet number:
1 out of 1
Revision:
2922
Designer:
Trym Snelltvedt
Date:
14-Jun-20
revolve
NTNU
No TVS diodes. This is a prototype board that will be used in a lab environment, ESD armbands or equivalents should be used when handling.
LOGO1
LOGO
Revolve Logo
J1A
J1B
ATSAM-on-Module
J2
J3
70 pin standard 2.54 mm pitch

B.2.2 Layout

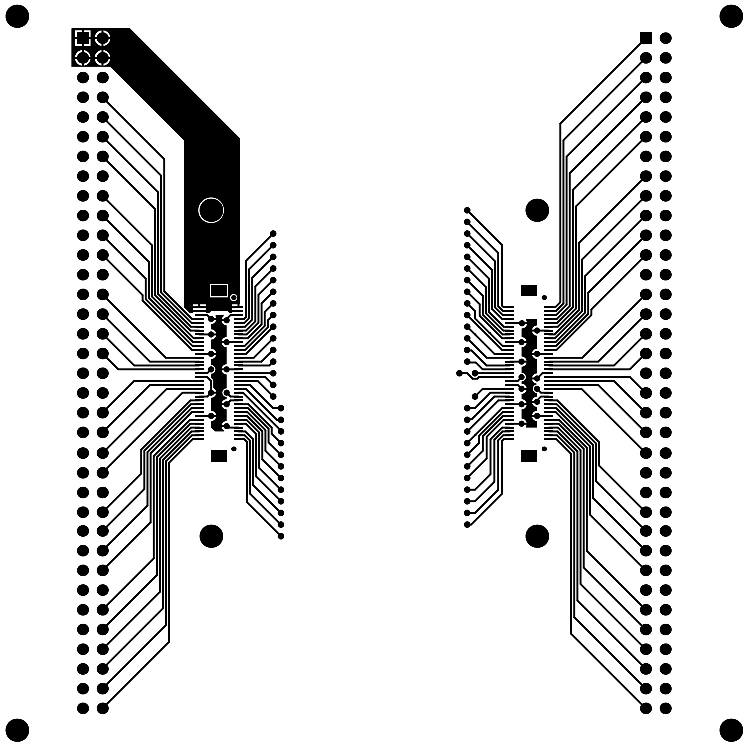


Figure B.5: Prototype carrier board top layer.

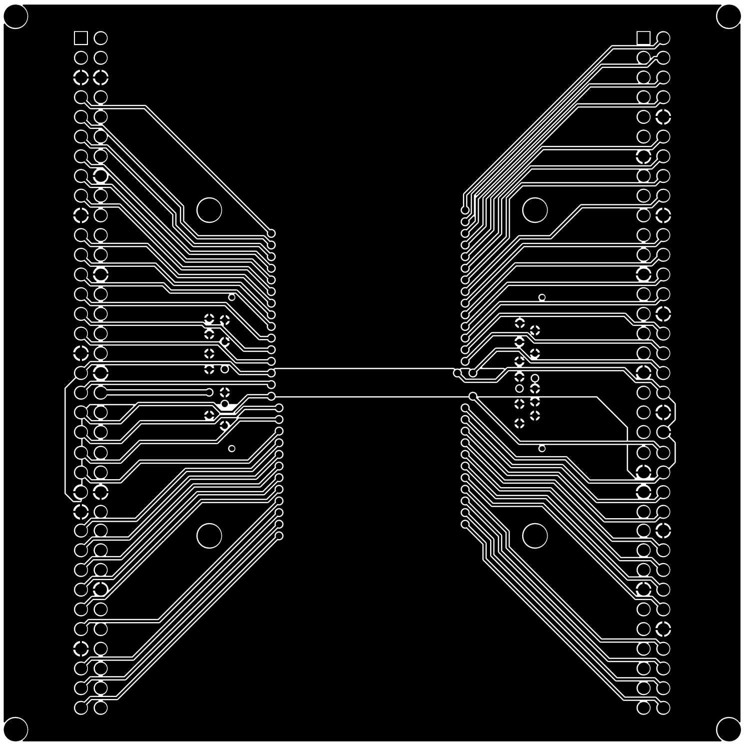
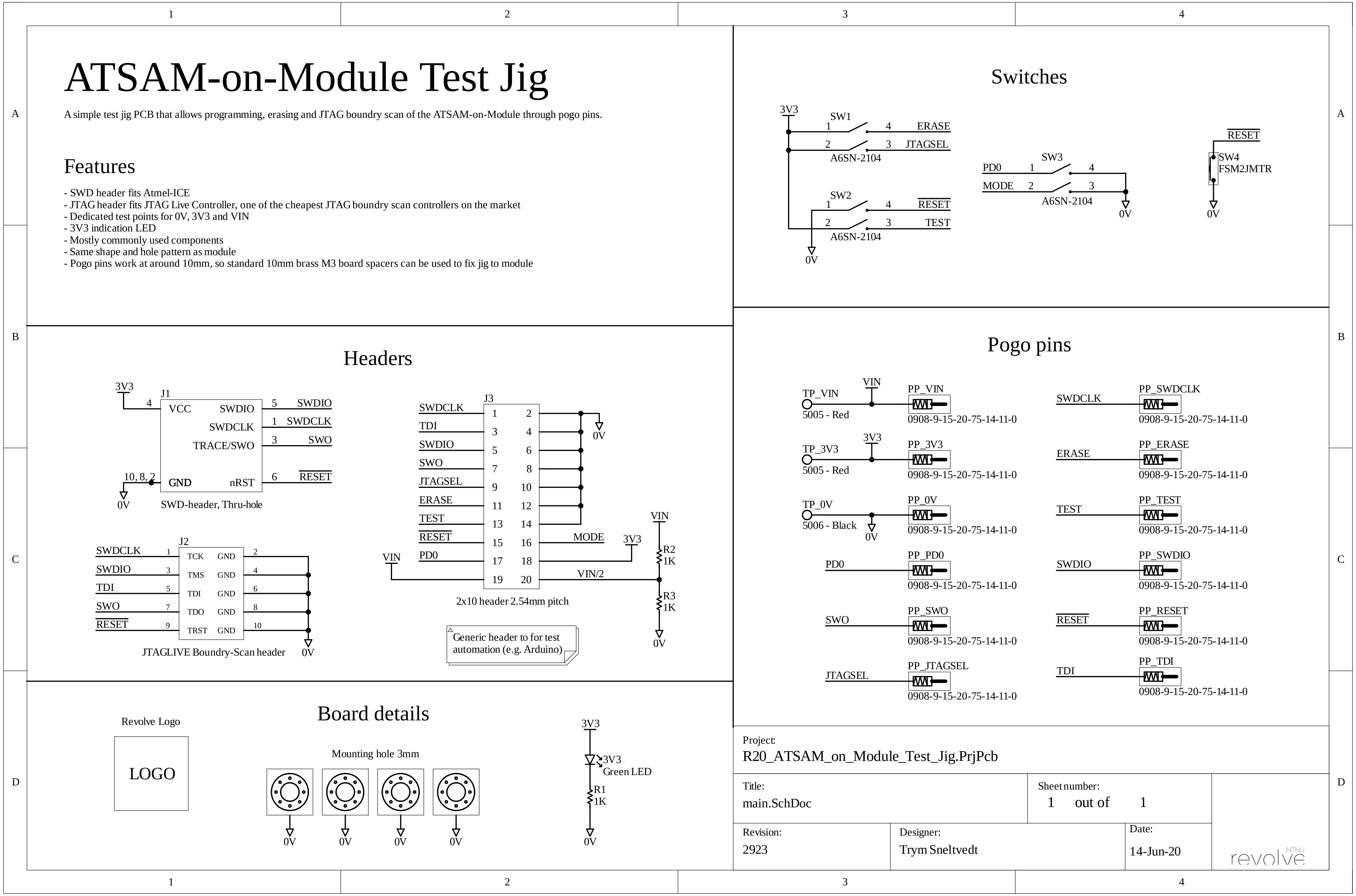


Figure B.6: Prototype carrier board bottom layer.

B.3 Test jig

B.3.1 Schematics



ATSAM-on-Module Test Jig
A simple test jig PCB that allows programming, erasing and JTAG boundry scan of the ATSAM-on-Module through pogo pins.
Features
- SWD header fits Atmel-ICE
- JTAG header fits JTAG Live Controller, one of the cheapest JTAG boundry scan controllers on the market
- Dedicated test points for 0V, 3V3 and VIN
- 3V3 indication LED
- Mostly commonly used components
- Same shape and hole pattern as module
- Pogo pins work at around 10mm, so standard 10mm brass M3 board spacers can be used to fix jig to module
Switches
3V3
SW1
ERASE
JTAGSEL
A6SN-2104
SW2
RESET
TEST
A6SN-2104
0V
SW3
PD0
MODE
A6SN-2104
0V
RESET
SW4
FSM2JMTR
0V
Headers
3V3
J1
VCC
SWDIO
SWDCLK
TRACE/SWO
GND
nRST
SWDIO
SWDCLK
SWO
RESET
10, 8, 2
0V
SWD-header, Thru-hole
J2
SWDCLK
SWDIO
TDI
SWO
RESET
TCK
TMS
TDI
TDO
TRST
GND
0V
JTAGLIVE Boundry-Scan header
J3
SWDCLK
TDI
SWDIO
SWO
JTAGSEL
ERASE
TEST
RESET
PD0
VIN
0V
MODE
3V3
VIN/2
2x10 header 2.54mm pitch
Generic header to for test automation (e.g. Arduino)
VIN
R2
1K
R3
1K
0V
Pogo pins
TP_VIN
5005 - Red
VIN
PP_VIN
TP_3V3
5005 - Red
3V3
PP_3V3
TP_0V
5006 - Black
0V
PP_0V
PD0
PP_PD0
SWO
PP_SWO
JTAGSEL
PP_JTAGSEL
SWDCLK
PP_SWDCLK
ERASE
PP_ERASE
TEST
PP_TEST
SWDIO
PP_SWDIO
RESET
PP_RESET
TDI
PP_TDI
0908-9-15-20-75-14-11-0
Board details
Revolve Logo
LOGO
Mounting hole 3mm
0V
3V3
3V3
Green LED
R1
1K
0V
Project:
R20_ATSAM_on_Module_Test_Jig.PrjPcb
Title:
main.SchDoc
Sheet number:
1 out of 1
Revision:
2923
Designer:
Trym Sneltvedt
Date:
14-Jun-20
revolve
NTNU

B.3.2 Layout

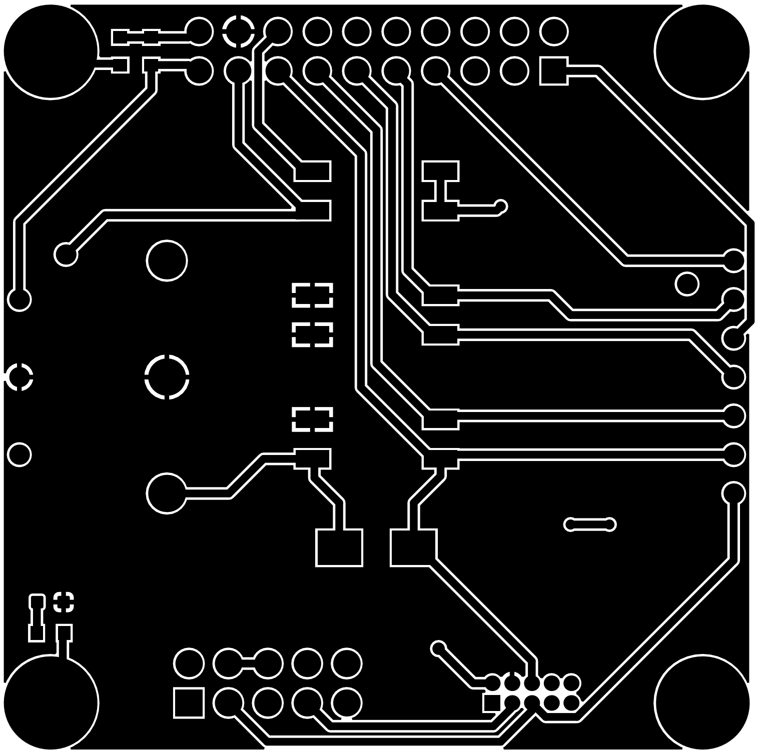


Figure B.7: Test jig top layer.

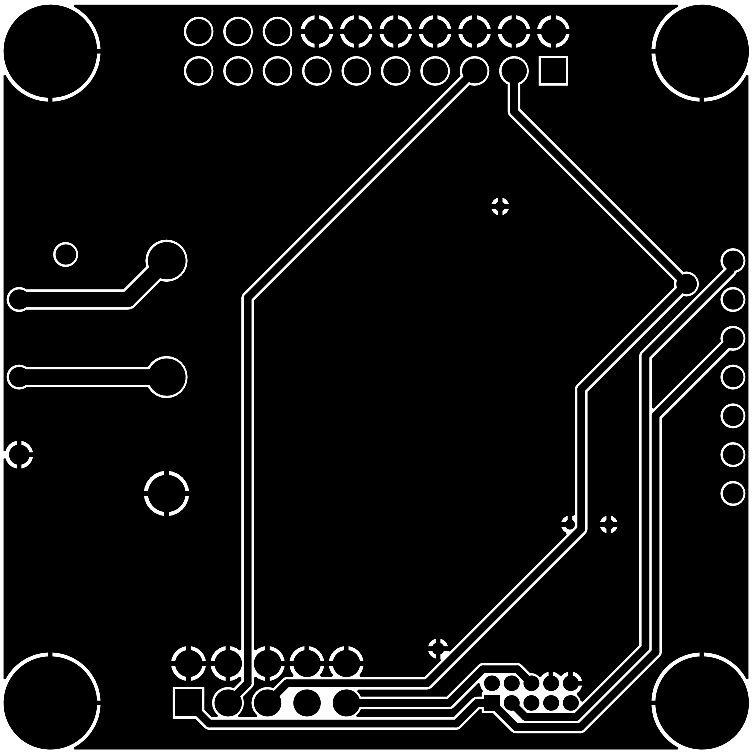


Figure B.8: Test jig bottom layer.

NTNU
Norwegian University of
Science and Technology