SUN DEVIL
ROCKETRY

Avionics Hardware Design Team

Liquid Engine Controller Hardware Documentation

PCB Part No.	L0002
Current Revision	5.1
Project:	Liquid Engine
Design Engineer(s)	Colton Acosta
Test Engineer(s)	Colton Acosta

TABLE OF CONTENTS

LISTING OF ALL ACRONYMS

Acronym	Definition
AC	Alternating Current (Voltage)
ARM	Advanced RISC Machines, refers to processor architecture
ADC	Analog to Digital Converter, refers to MCU peripheral
DC	Direct Current
ESR	Equivalent Series Resistance (Capacitor/Inductor Specification)
GPIO	General Purpose Input Output, refers to MCU pin configuration
I2C	Inter-Integrated Circuit, serial communication protocol
IC	Integrated Circuit
IDC	Insulation-Displacement Contact, refers to cable header and harness assembly

IO	Input/Output
LED	Light-Emitting Diode
RTC	Real Time Clock, refers to MCU peripheral
MCU	Microcontroller
NC	Not connected
PC	Personal Computer (Not an embedded computer)
PCB	Printed Circuit Board
PWM	Pulse Width Modulation, refers to both the MCU peripheral and process of pulsing a voltage high and low at a predetermined rate and duty cycle
PWR	Power
RGB	Red, Green, Blue
RMS	Root Mean Squared
SDR	Sun Devil Rocketry
SWD	Serial Wire Debug, refers to MCU programming and debug interface/pins
UART	Universal Asynchronous Receiver-Transmitter, refers to MCU peripheral
USB	Universal Serial Bus

PCB NAMING CONVENTIONS

All PCBs designed by Sun Devil Rocketry follow the same five character naming convention. Each board has its own unique part number which consists of a letter followed by a four digit number. The letter indicates the project focus, and the number indicates the order in which the boards were designed with lower numbers being assigned to older boards. The letter designations are listed in the table below.

Sun Devil Rocketry PCB Letter Designations

Letter	Definition

A	Avionics - General purpose boards to be used internally by the avionics team or non-propulsion avionics projects
H	Hybrids - Boards used in the projects of the hybrid propulsion team
L	Liquids - Boards used by SDR's liquid engine
S	Solids - Boards used by the solid propulsion team's projects

A complete listing of all Sun Devil Rocketry PCBs can be found on the Sun Devil Rocketry website.

PCB DESIGN FILES

The working directory for the L0002 design files can be found here for Sun Devil Rocketry members. The most up-to-date design files can also be downloaded by anyone on the Sun Devil Rocketry GitHub (link).

1. DESIGN OVERVIEW:

The Liquid Engine Controller (L0002) is the main processor for managing the engine hardware of SDR's experimental liquid bipropellant rocket engine. The controller is responsible for valve actuation/sequencing, sensor monitoring, data logging, and telemetry. The system requirements for the controller are as follows:

1. The engine controller shall be capable of issuing solenoid actuation commands and keeping track of solenoid actuation states.
2. The engine controller shall be capable of issuing commands for servo actuation and monitoring ball-valve actuation states
3. The engine controller shall be capable of reading at least 10 analog sensor outputs including outputs from pressure transducers, thermocouples, load cells, and strain gauges.
4. The engine controller shall be capable of implementing a sequencing of valves with at least 1 ms of timing resolution/accuracy.

5. The engine controller shall be capable of transmitting/receiving telemetry at a distance of at least 200 feet.

6. The engine controller shall be capable of providing 2A of current to the main engine ignition charge with a minimum power supply of 12V.

7. The engine controller shall be capable of recording data from sensors during operation in non-volatile memory.

8. The engine controller shall be capable of performing the ignition and propellant injection sequence autonomously.

Due to the relatively large size of the static test cart, no strict form factor specifications are enforced. Additionally, no strict power consumption specifications were enforced since the electronics will be powered with a generator. Design decisions were made with priority given to cost, speed, accuracy, manufacturability, complexity, and reliability.

2. CONTROLLER ARCHITECTURE:

The high-level functionality of the engine controller hardware is defined by the block diagram shown in Fig. 2.1. The information and power relationships between each component/subsystem are denoted by the arrows with the indicated directionality.

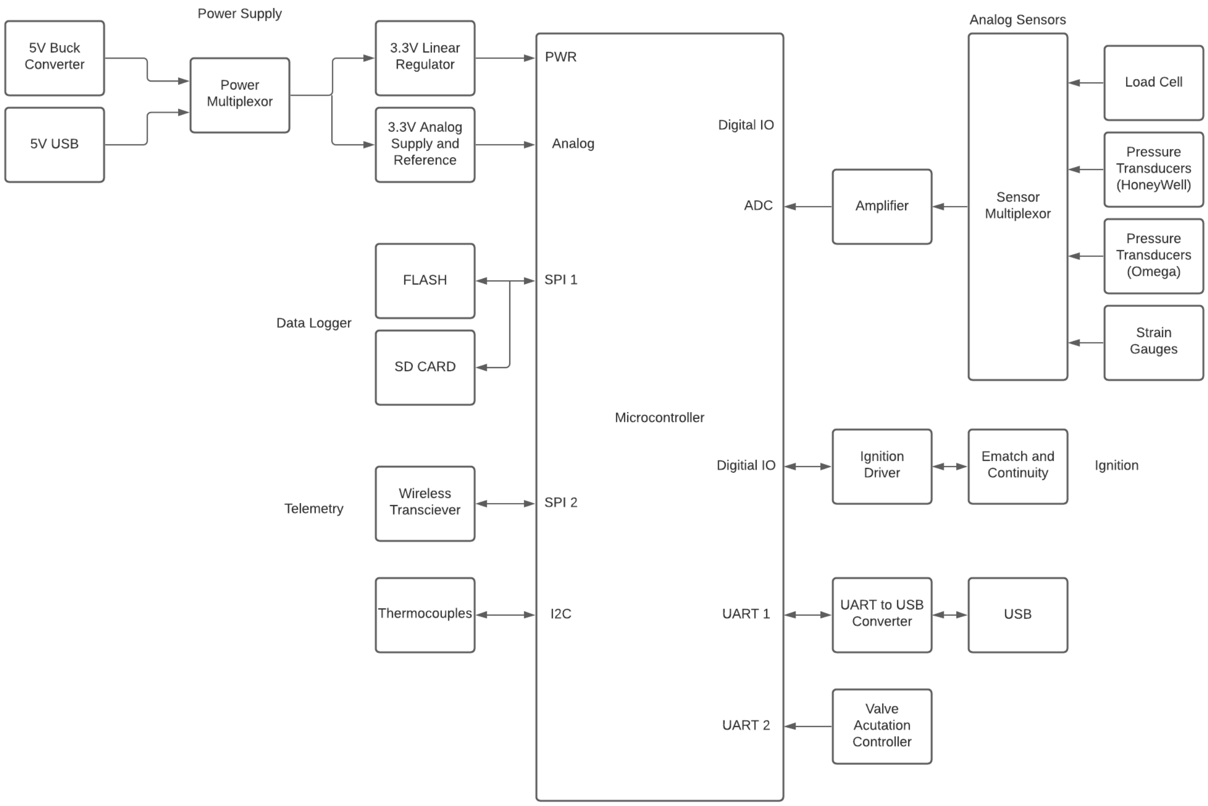


Figure 2.1 Liquid Engine Controller Architecture Diagram

The valve controller (L0005) is an external piece of hardware; the block on the diagram refers to the controller's communication interface.

3. POWER SUPPLY:

5V Buck Converter:

The liquid engine controller will be powered during the hotfire test using a generator that produces a 120V RMS AC supply voltage. The 120V AC supply will be converted to DC and dropped to a lower voltage using an external power supply module. While the external module will drop the voltage significantly to power the engine controller, it is desirable to further regulate the supply voltage on the controller board in order to make the board compatible with a wide range of supply voltages. For this reason, the engine controller includes an embedded 5V buck converter to regulate the main supply voltage that powers onboard hardware and connected external modules such as the valve controller (L0005), photogate sensors (L0004), pressure transducers, and load cells. The 5V output was chosen to be compatible with the supply voltage used to calibrate the engine's pressure transducers. The typical application schematic included in the buck converter datasheet is shown in Fig. 3.1, and the hardware specifications of interest are listed in Table 3.1. The specific buck converter IC was chosen based on its power capability and high availability at the time of design.

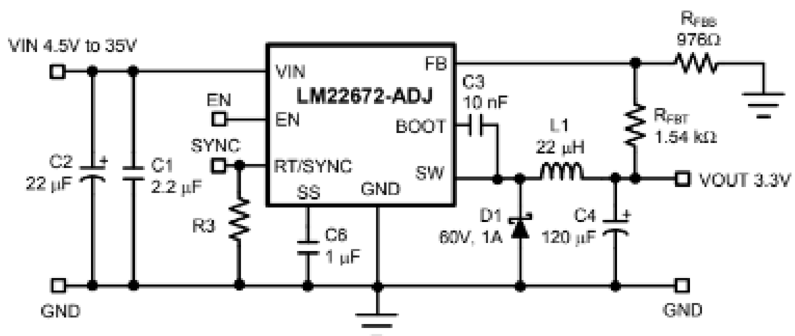


Figure 3.1 Buck Converter Application Schematic (Datasheet pg. 17)

Table 3.1. Buck Converter Electrical Specifications

Specification	**Value**
Output Configuration	Step-Down, Positive, Fixed
Minimum Input Voltage	4.5V
Maximum Input Voltage	42V
Output Voltage	5V
Switching Frequency	500kHz
Output Current	1A

The buck converter application schematic is shown in Fig. 3.2.

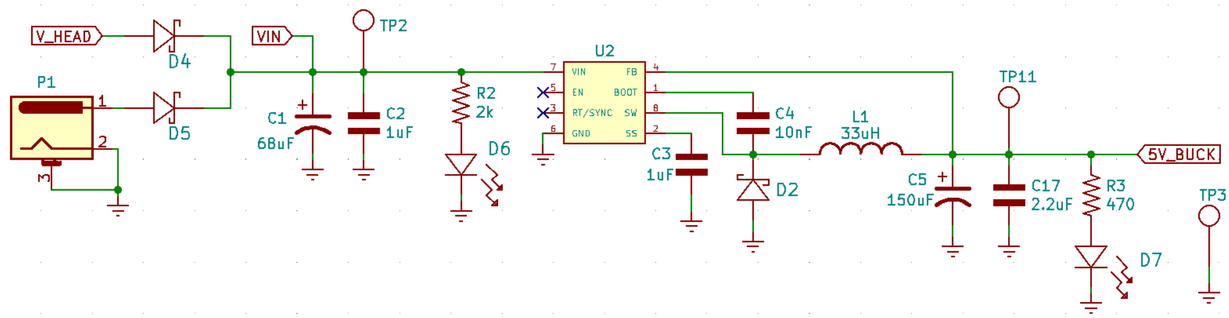


Figure 3.2. Buck Converter Application Schematic

<u>LEDs/Input Sources:</u>

The input to the buck converter is ORed between a connector supply pin and a 12V barrel jack to allow the controller to be powered either from an external supply or a 12V DC adapter. The schottky diodes in series with the supply lines protect the board from a short-circuit in the event that both supply sources are present. The circuit includes two indication LEDs that indicate when power is present on the buck converter's input and output rails. The current limiting resistors were chosen to make the LED current approximately 5mA. For the input supply LED, the resistance was chosen assuming the supply line is at 12V. Even at the maximum input supply voltage (42 V), the LED current is less than the maximum of 25 mA (see Datasheet).

<u>Chip Configuration:</u>

The buck converter operating configuration is set by the external components attached to the EN, RT/SYNC, and SS pins. The enable pin (EN) is left floating in order to keep the regulator on when a supply voltage is applied. The buck converter has an internal pull-up resistor which allows the pin to be left floating. Similarly, the RT/SYNC pin is left floating to keep the switching frequency of the buck converter at the default of 500 kHz. The soft-start pin (SS) controls the rate at which the buck converter reaches steady regulation when a supply voltage is applied. The datasheet (pg. 9) recommends a value in the range of 100 nF to 1 uF. A 1 uF capacitor is used to reduce transient stresses as much as possible. The soft-start time is given below:

$$T_{SS} = 26{,}000 C_{SS} = 26 \text{ ms}$$

The capacitor between the BOOT and SW pins is used to power internal circuitry in the buck converter. The datasheet (pg. 11) recommends a ceramic 10nF capacitor with short, wide PCB traces. Since the fixed 5V output chip is being used, the FB pin is connected directly to the output. This allows the internal compensator to correctly regulate to 5V. Other chips in the product family have adjustable output, which is set using a resistor divider connected to the FB pin.

Power Component Sizing:

The power diode (D2 in Fig. 3.2) was selected based on the maximum input voltage and average load current. The datasheet (pg. 17) recommends a reverse voltage rating 1.3 times the maximum input voltage. For the maximum input voltage of 42V, a reverse rating of 60V provides a healthy safety margin. The current rating of the diode was chosen to be 1A to match the current rating of the buck converter. A schottky diode is used for its low voltage drop under load.

The inductor was chosen based on output ripple current considerations. The datasheet (pg. 18) advises that choosing an inductor with peak-to-peak current ripple around 30% of the nominal output current provides a good compromise between excessive voltage ripple and excessive component size and cost. The inductance is calculated using Eq. 13 of the datasheet, as shown below:

$$L = \frac{(V_{in} - V_{out})V_{out}}{0.3 I_{out} f_{SW} V_{in}}$$

$$L = \frac{(42\text{V} - 5\text{V})(5\text{V})}{0.3(1\text{A})(500 \times 10^3)(42\text{V})} = 29.3\,\mu\text{H}$$

The current ripple at the maximum input voltage is then calculated as follows:

$$\Delta I = \frac{(V_{in} - V_{out})V_{out}}{L f_{SW} V_{in}}$$

$$\Delta I = \frac{(42\text{V} - 5\text{V})(5\text{V})}{(33 \times 10^{-6}\text{H})(500 \times 10^3\text{s}^{-1})(42\text{V})} = 267\text{ mA}$$

The peak current is then,

$$I_{peak} = I_{av} + \frac{\Delta I}{2} = 1.133\,\text{A}$$

The chosen inductor is rated for 3.5 A, which is well above this value. The output capacitors are chosen based on output voltage ripple and stability considerations. The datasheet (pg. 19) recommends a value of 100uF or greater. A parallel combination of electrolytic and ceramic capacitors is used to supply current during transient events and reduce output noise and ripple. The ripple is limited by the ceramic capacitor, and the bulk electrolytic capacitor supplies the transient currents. The worst-case output ripple voltage is calculated below:

$$V_{ro} = \frac{(V_{in} - V_{out})V_{out}}{8V_{in}} \frac{1}{f_{SW}^2 L C_{out}}$$

$$V_{ro} = \frac{(42\text{V} - 5\text{V})(5\text{V})}{8(42\text{V})} \frac{1}{(500 \times 10^{-3}\text{s}^{-1})^2 (33 \times 10^{-6}\text{H})(2.2 \times 10^{-6}\text{F})} = 30.3\text{mV}$$

The output capacitance also affects the stability of the internal compensator. According to the datasheet, the second order pole of the transfer function should be placed between 1.5 and 15 kHz (Datasheet pg. 12). The pole is calculated as follows:

$$f_o = \frac{1}{2\pi\sqrt{LC_{out}}}$$

$$f_o = \frac{1}{2\pi\sqrt{33 \times 10^{-6}\text{H}(152.2 \times 10^{-6}\text{F})}} = 2246\text{ Hz}$$

Similar to the output capacitors, the input capacitors were chosen to minimize the input ripple and supply current during transient events. For the low ESR ceramic capacitor, the datasheet (pg. 19) recommends a value between 0.47 and 1 uF. The input voltage ripple is given by the following, where the input capacitance is the equivalent capacitance of the parallel configuration shown in Fig. 3.2:

$$V_{ri} = \frac{I_{out}}{4 f_{SW} C_{in}}$$

$$V_{ri} = \frac{1\text{A}}{4(500 \times 10^{3}\text{s}^{-1})(69\mu\text{F})} = 7.2\text{ mV}$$

The RMS current is approximately,

$$I_{RMS} = \frac{I_{out}}{2} = 500\ \text{mA}$$

The chosen capacitor has a maximum current rating of 600 mA, so it should work for this application. Finally, the maximum output current is a function of the switching frequency and inductor selection. The worst-case maximum current is given by the following:

$$I_{out}|_{max} = I_{CL} - \frac{(V_{in} - V_{out})V_{out}}{2L f_{SW} V_{in}}$$

$$I_{out}|_{max} = 1.2\text{A} - \frac{(42\text{V} - 5\text{V})5\text{V}}{2(33 \times 10^{-6}\text{H})(500 \times 10^{3}\text{s}^{-1})(42\text{V})} = 1.07\ \text{A}$$

3.3V Supply:

The engine controller's microcontroller requires a 3.3V supply to operate, which is delivered from a linear 3.3V regulator powered by the 5V supply rail. To allow the regulator to be supplied from several 5V sources, a power multiplexor is used that automatically switches between 5V sources based on whether or not power is present on the rail. The multiplexor and linear regulator application schematic is shown in Fig. 3.3.

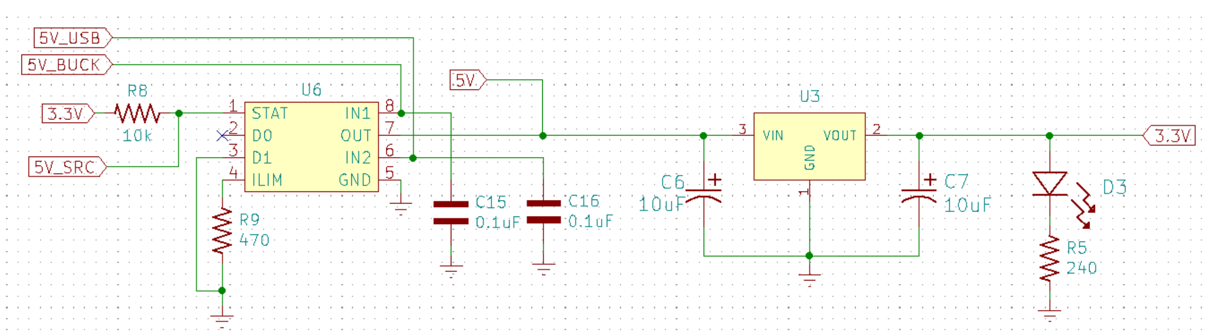


Figure 3.3 Power Multiplexor and 3.3V Linear Regulator

An indication LED is used on the 3.3V power line to visually indicate when power is on the rail. The current limiting resistor was chosen to limit the LED current to approximately 5mA. The regulator can supply up to 1.2A. Two 10uF tantalum capacitors are used at the regulator input and output pins to enhance the regulator's stability and transient response, as recommended in the device datasheet.

The power multiplexer supplies the 3.3V regulator using either the 5V output of the buck converter or the 5V USB rail. The D0 and D1 pins set the switching mode of the multiplexor. Setting D0 disconnected and D1 grounded puts the multiplexor in auto-switching mode. In this mode, the multiplexer passes the IN1 voltage to the output by default. If the IN1 voltage falls below ~2.5V, the multiplexor will pass the IN2 voltage to the output if it is greater than ~2.5V. This effectively prioritizes the buck converter power supply over the USB rail, to allow the USB supply current to be minimized when large current draw is required by the controller. The USB supply is mainly for use when communicating with a PC, to make software development more convenient by limiting the amount of external circuitry required to power the board. Both input voltage pins are decoupled using 0.1 uF ceramic capacitors placed close to the chip in the PCB layout. This suppresses noise and inductive spikes on the input rails that can influence the multiplexor switching or damage the device.

The ILIM pin controls the current-limiting capability of the multiplexor. The relationship between the maximum output current and the pull-down resistance is given in pg. 17 of the datasheet. The resistor chosen in this application was chosen arbitrarily to make the current limit close to the maximum current of the device, as the datasheet (pg. 17) advises against disabling the current-limiting feature by shorting the ILIM pin to ground. The STAT pin indicates which supply voltage is passed to the multiplexer output. The multiplexor grounds the STAT pin when the IN1 voltage is passed to the output, and floats the STAT pin when IN2 is used. The pull-up resistor on the STAT pin ensures that the 5V_SRC signal goes high when the IN2 supply is used.

Microcontroller Power Supply Scheme:

In order to ensure the MCU receives a stable voltage from the regulator circuit despite the presence of parasitics present in the PCB routing, a number of ceramic, low-ESR, decoupling capacitors are used as recommended by the datasheet. In the PCB layout design, they are placed as close to the MCU pins as possible in order to minimize the trace lengths. The number of decoupling capacitors and the capacitance of each were chosen according to the datasheet recommendations. The recommended connections and capacitances are shown in Fig. 3.4. These capacitors are grouped together on the schematic to save whitespace, and are shown in Fig. 3.5.

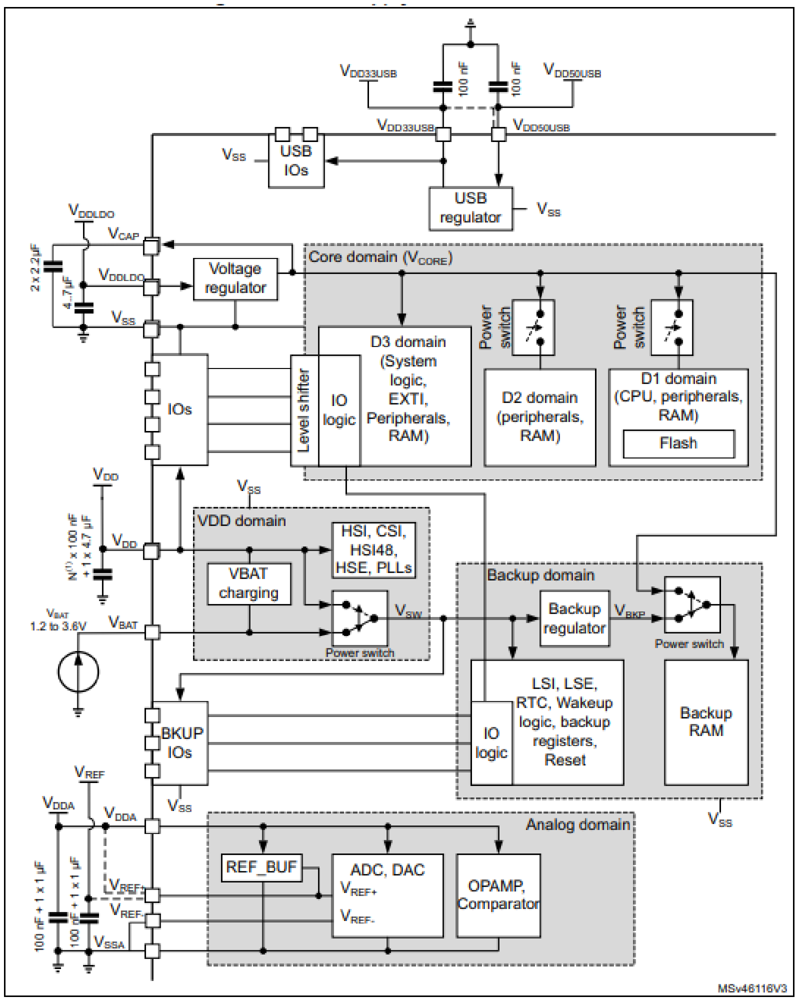


Figure 3.4 MCU Power Supply Scheme (Datasheet 6.1.6, pg. 92)

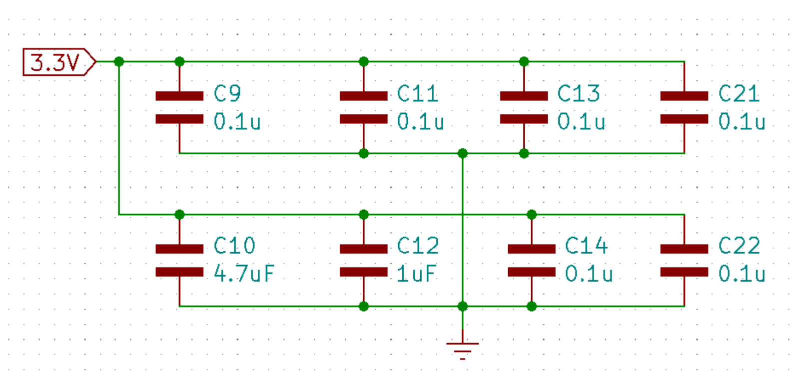


Figure 3.5. Microcontroller Decoupling Capacitors in Schematic

The USB and VDDLDO pins shown in Fig. 3.4 are not included with the chosen MCU, and therefore these capacitors are left out of the schematic. Additionally, the internal regulator of the MCU requires external 2.2 uF low ESR ceramic capacitors for stability (Datasheet 6.3.2 pg. 96). These capacitors are grouped separately from the decoupling capacitors to distinguish them from the other MCU capacitors, although they are also placed very close to the MCU in the PCB layout. The MCU stability capacitors' schematic are shown in Fig. 3.6.

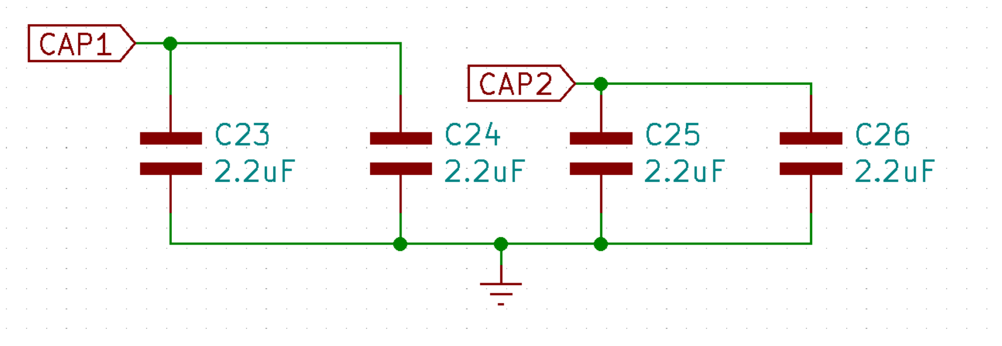


Figure 3.6. MCU Regulator Stabilization Capacitors

4. MICROCONTROLLER:

The engine controller uses an STMicroelectronics STM32H750VBT6 microcontroller, with a single-core ARM Cortex-M7 processor. The MCU was chosen for its maximum clock speed of 480 MHz, since the timing of the engine sequencing is a critical performance factor that influences design decisions. Although the MCU has limited availability and a high per-unit price, the thorough documentation available offsets these costs. The peripheral usage of the MCU is given in Table 4.1.

Table 4.1 Microcontroller Peripheral Functionality

Peripheral	**Usage**
Pulse Width Modulation (PWM)	Sets the color of the firmware status LED
Timer	Triggers the execution of precise engine sequencing operations
Analog to Digital Converter (ADC)	Reads pressure transducer, load cell, and strain gauge

	sensor data
Universal Asynchronous Receiver Transmitter (UART)	Valve controller (L0005) serial communication, USB PC communication
Inter-Integrated Circuit (I2C)	Communication with thermocouple cold-junction compensation chip
Serial Peripheral Interface (SPI)	Data logging on flash and SD card external memory devices, Wireless Interface
General Purpose Input/Output (GPIO)	Ignition, power indication, amplifier gain selection

Programmer:

The MCU is programmed using an SWD interface and the standard 20 pin ARM IDC programming cables. The programmer used is the ST-Link V2 (source), chosen for its affordability and compatibility with ST microcontrollers. A 0.05” (1.27mm) pitch mating IDC connector is used for its small form factor, which requires an adapter (A0004) to connect to the 0.1” (2.54mm) IDC header on the ST-Link.

Figure 4.1 ST-Link V2 Programmer

Figure 4.2 IDC Programming Cable

The SWD pinout of the ST-Link V2 is shown in Figure 4.3, which is taken from the ST-Link datasheet (pg. 13). The “Not Connected” pins are used for JTAG, and therefore are not needed for this application. The ST-Link pins used during SWD programming and debugging are listed in Table 4.2.

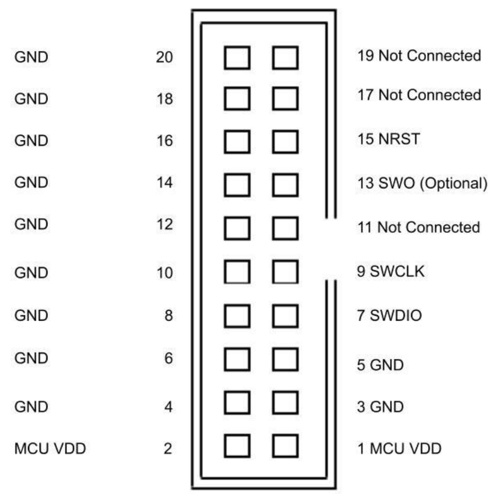


Figure 4.3. ST-Link V2 Programmer Pinout

Table 4.2. ST-Link V2 SWD Pinout Descriptions (ST-Link datasheet, pg. 12)

Pin Number	Name	Description
1-2	MCU VDD	Target reference voltage, connected to MCU supply voltage (3.3V)
7	SWDIO	Bi-directional data, pulled up to 3.3V
9	SWCLK	Clock signal, pulled up to 3.3V
13	SWO	Serial Wire Output trace port
15	NRST	Reset signal, active low

The programmer schematic is shown in Fig. 4.4. The SWDIO and SWCLK signals use 100 kOhm pull up resistors as recommended by the MCU reference manual (pg. 3061).

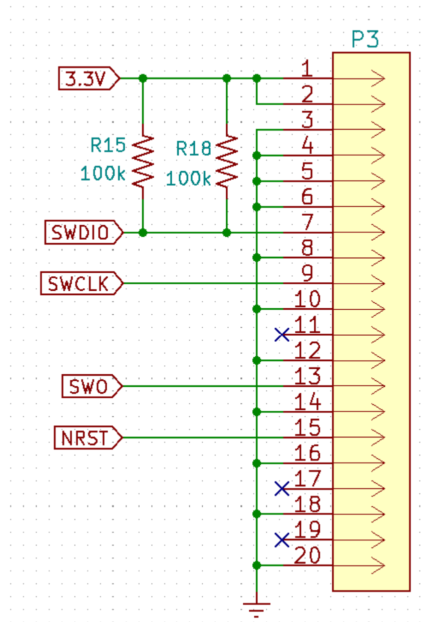


Figure 4.4 SWD Programming Connector Schematic

Microcontroller Pinout:

The MCU pinout provided in the MCU datasheet (pg. 53) is shown in Fig. 4.5.

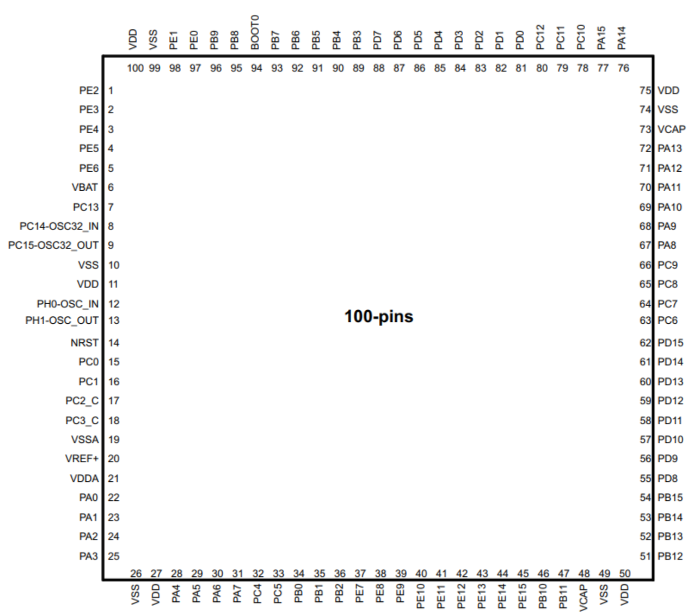


Figure 4.5 Microcontroller Pinout (MCU datasheet, pg. 53)

To improve the readability of the MCU schematic and PCB layout, each MCU pin used in the design is attached to a global net label. The labels used are shown in the MCU schematic shown in Fig. 4.6, and are listed in Table 4.3. Enumerated signals in Table 4.3 use lowercase "n" to indicate the signal number. The signals detailed in Table 4.3 can also be found in a google sheets "cheat sheet" in the L0002 design folder for more convenient access and reference.

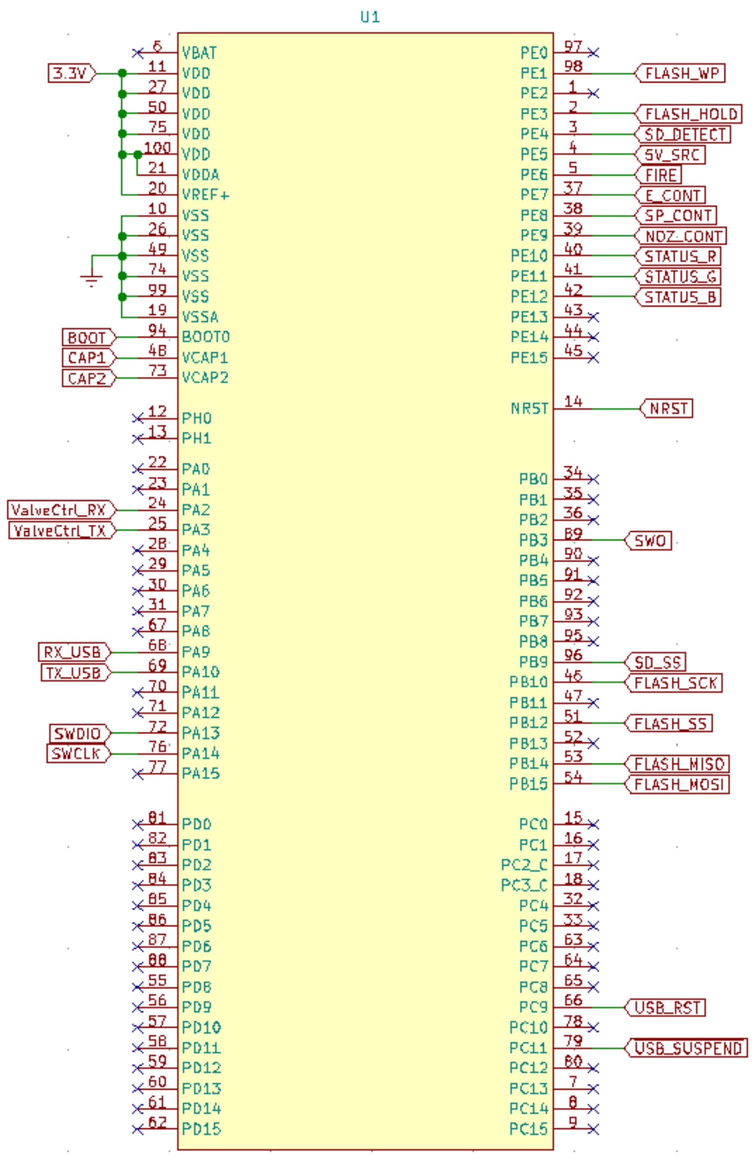


Figure 4.5. Microcontroller Schematic

Table 4.3 Microcontroller Signal Names and Definitions

Signal Name	**Signal Type**	**Definition**
5V_SRC	Digital Input	Indicates which 5V power supply is being used by the multiplexer.
BOOT	Digital Input	MCU boot mode, high signal prompts MCU to run code from boot loader memory instead of main program flash
CAPn	Power	Internal regulator stability capacitors. See “Microcontroller Power Supply Scheme” in section 3 for more details. n = 1 or 2
E_CONT	Digital Input	Indicates Ematch Continuity. High for continuity, grounded when ematch is disconnected
FIRE	Digital Output	Ignites Ematch to ignite Solid Propellant Slug. 3.3V Signal pushes current through power MOSFET to Ematch
FLASH_HOLD	Digital Output	Flash HOLD mode signal
FLASH_MISO	Serial Communication	Data logger SPI master (MCU) input, slave output line
FLASH_MOSI	Serial Communication	Data loggerSPI master (MCU) output, slave input line
FLASH_SCK	Serial Communication	Data logger SPI clock line
FLASH_SS	Serial Communication	Flash chip slave select line (SPI network)
FLASH_WP	Digital Output	Flash write protect
NOZ_CONT	Digital Input	Indicates Continuity of Nozzle Wire. Gets pulled high when nozzle exhaust burns through wire
NRST	Digital Input	MCU reset, active low

RX_USB	Serial Communication	UART to USB Serial Transmission, MCU Transmit, USB Host Receive
SD_DETECT	Digital Input	Indicates when an SD card is inserted in the SD card jack. Pulled low when SD card is inserted.
SD_SS	Serial Communication	SD card slave select line (SPI network)
SP_CONT	Digital Input	Indicates Continuity of solid propellant wire. Gets pulled high when solid propellant burns through wire
STATUS_R	Digital Output	Firmware status LED. Controls the red value of the status LED
STATUS_G	Digital Output	Firmware status LED. Controls the green value of the status LED
STATUS_B	Digital Output	Firmware status LED. Controls the blue value of the status LED
SWCLK	Serial Communication	SWD programming clock signal, generated by programmer (ST-Link)
SWDIO	Serial Communication	SWD programming data line
SWO	Serial Communication	SWD serial trace signal
TX_USB	Serial Communication	UART to USB Serial Transmission, MCU Receive, USB Transmit
~USB_RST	Digital Output	Resets the USB transceiver, active low, open drain
~USB_SUSPEND	Digital Input	Driven low by USB transceiver when controller enters the suspend state
ValveCtrl_RX	Serial Communication	Valve control UART receiver. Receives UART responses from the valve controller (L0005)
ValveCtrl_TX	Serial Communication	Valve control UART transmitter. Issues valve control commands to be executed by the valve controller (L0005)

LED Indication:

The status of the MCU firmware is visually displayed using the status LED and signals. The status LED is an RGB LED controlled by PWM signals that allow the LED to display any arbitrary RGB color. The status LED schematic is shown in Fig. 4.6.

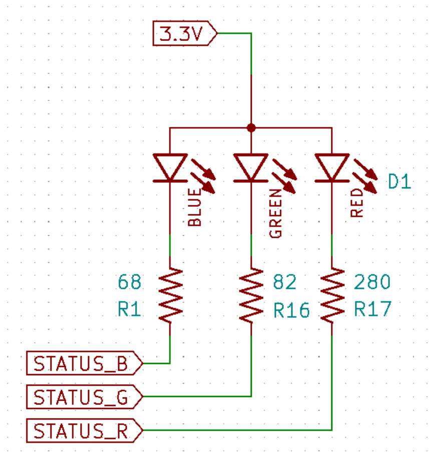


Figure 4.6. Firmware Status LED Schematic

Microcontroller Reset:

The microcontroller reset pin is driven by the SWD programmer and a tactile button that allows the MCU to be reset without removing the power supply. A 0.1 uF ceramic capacitor is used to prevent unwanted MCU resets due to voltage spikes on the reset pin. The button is disabled by default, and is enabled by closing the jumper with a solder bridge. The reset circuit is shown in Fig. 4.7.

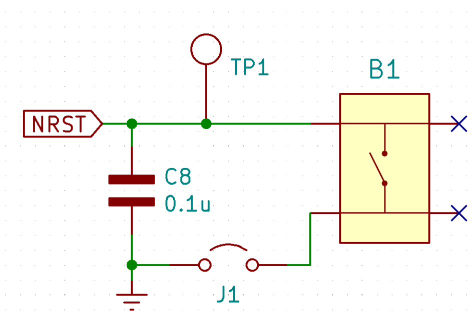


Figure 4.7. Microcontroller Reset Button

USB Interface:

The engine controller uses a USB interface to directly communicate with PCs. The USB interface allows for easy and unrestricted access to the engine controller state and hardware. Since the chosen MCU does not include a USB interface, an external USB transceiver is used which converts UART serial data from the MCU to the USB protocol. The transmitted data is then read by the PC by monitoring the relevant serial port. The USB transceiver schematic is shown in Fig. 4.8.

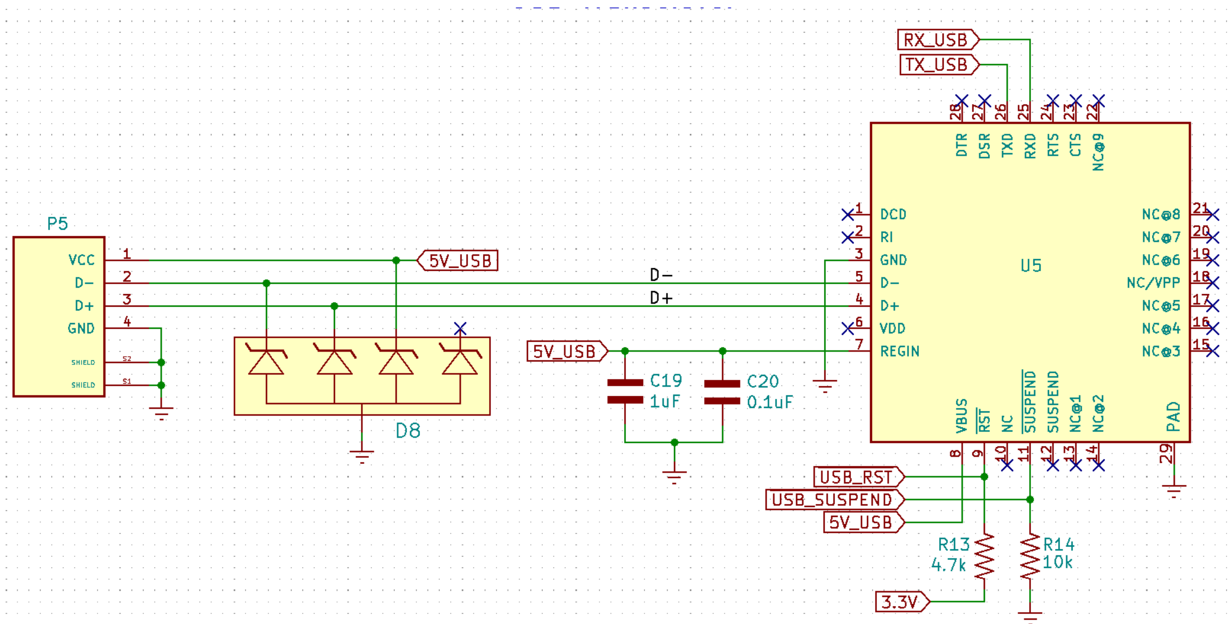


Figure 4.8. UART to USB Converter Schematic

The transceiver is powered by the USB 5V rail, and the transceiver's internal regulator is decoupled using two ceramic capacitors with values recommended by the transceiver datasheet (pg. 14). The transceiver is compliant with the USB 2.0 specification, and transmits/receives USB packets at a data rate of 12 Mbps. The RST and SUSPEND pins are used to control/monitor the behavior of the USB transceiver. A low voltage to RST will reset the transceiver, and the pin is pulled up to 3.3V by a 4.7 kOhm resistor to increase noise immunity as recommended by the transceiver datasheet (pg. 14). The SUSPEND pin is driven low when the USB transceiver enters suspend mode. The suspend pin is pulled down to ground with a 10 kOhm resistor to prevent the suspend signal from being asserted when the transceiver is reset (datasheet pg. 14). The transceiver is protected from ESD by the zener diode array connected to the USB signals.

To ensure the USB signals are not corrupted by reflections on the data transmission lines, the USB D+ and D- traces are designed to have a characteristic differential impedance of 90 Ohms at the transmission frequency of 12 MHz. The trace specifications were calculated using KiCad's impedance calculator. Since the PCB dielectric is FR-4, the dielectric constant is 4.5, and the loss tangent is 0.02. The traces are copper, so the resistivity is 1.72e-8 Ohms/m. The dielectric height is calculated from the PCB thickness and number of layers to be 0.533 mm, since the controller is 1.6 mm thick and has 4 layers. The spacing between the differential traces was chosen to be 3.5 mil, since this is the minimum trace thickness that is supported by JLCPCB. The trace widths were then calculated to make the trace differential impedance as close to 90 Ohms as possible. A screenshot of the KiCad impedance calculator is shown in Fig. 4.9.

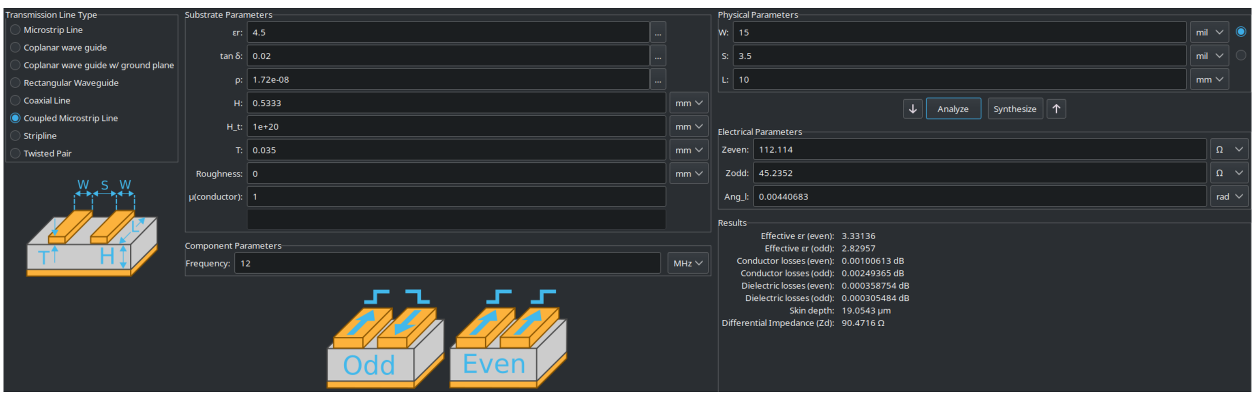
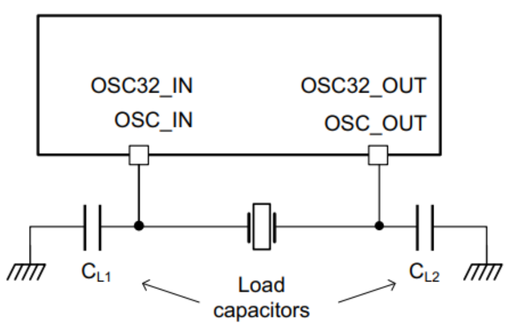


Figure 4.9. USB Transmission Line Impedance Calculations

External Oscillator:

MCU Reference Manual pg. 336



MCU Datasheet pg. 28: Crystal oscillator of 4-48 MHz

Crystal increases the accuracy of the clock and hence the timers.

Load Capacitance: 18pF (Crystal Datasheet, with part number)

Parasitic MCU capacitance: Datasheet recommends 10 pF

$$C_L = \frac{C_1 C_2}{C_1 + C_2} + C_{stray}$$

$$C_L = \frac{C}{2} + C_{stray}$$

$$C = 2(C_L - C_{stray}) = 2(18\,\mathrm{pF} - 10\,\mathrm{pF}) = 8\,\mathrm{pF}$$

5. DATA LOGGER:

External Flash:

- Active low slave select signal, high to low transition on CE pin activates the chip
- 8 bit data transfers for opcode, address, and data
- Inputs accepted on rising edge of the CLK
- Data transfer starts with MSB (most significant bit)
- Chip supports either active high or active low clk signal
- Low idle clock is used with 10k pull down resistor (MCU CPOL bit 0)
- Rising edge of clock with low idle clock makes MCU CPHA bit 0 (1 edge)
- Open drain slave select pin to make slave select default high

SD Card:

- SDMMC MCU interface
- 4 push-pull data lines: SDMMC_D[3:0] (MCU Reference Manual pg. 2405)
- Data flow direction pins are not used: SDMMC_D0DIR, SDMMCD123DIR (MCU Reference Manual pg. 2405)

- Command/Response Signal is push-pull: SDMMC_CMD (MCU Reference Manual pg. 2405)
- Command/Response direction signal is not used: SDMMC_CDIR (MCU Reference Manual pg. 2405)
- Clock signal is SDMMC_CK (MCU Reference Manual pg. 2405)
-

6. TELEMETRY:

7. ACTUATION INTERFACE:

8. SENSORS:

Thermocouple:

The liquid engine uses a thermocouple mounted at the top of the liquid oxygen tank to measure the temperature of the liquid oxygen and provide indication when the tank is full during the fill procedure. For high accuracy at low temperatures, a type-T thermocouple is used. The thermocouple output ranges from -5.6mV to 20.81mV (MCP96L01 datasheet pg. 4) over the range of measurable temperatures, which requires that the output be amplifier prior to its measurement by the MCU ADC with a 3.3V reference voltage. Additionally, the contact between the thermocouple leads and the crimp contacts of the connector creates a cold-junction interface that introduces error in the temperature measurement. To amplify the thermocouple output and compensate for cold-junction error a specially designed IC (MCP96L01) is used to digitize the thermocouple output, perform the necessary cold-junction compensation calculations, and transmit the data serially to the MCU. The schematic capture of the cold-junction compensation IC and thermocouple connector is shown in Fig. 8.1.

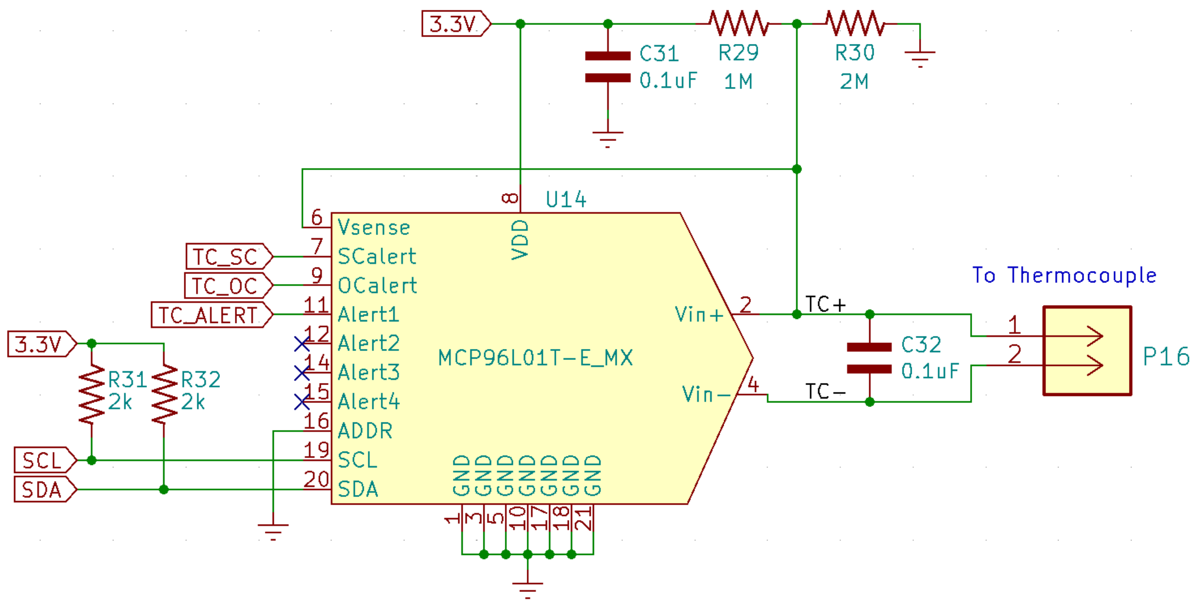


Figure 8.1. Thermocouple Cold-Junction Compensation IC Schematic

The connector P16 connects directly to the thermocouple leads and delivers the raw signal to the PCB traces. The 0.1µF capacitor decouples the power supply to the IC. The Vsense pin monitors the voltage on the positive thermocouple output in order to monitor the thermocouple operation. Another 0.1µF capacitor is connected between the thermocouple leads to prevent false triggering of the fault indicator signals. The resistor network configuration is specified by the MCP96L01 datasheet (pg. 7, Figure 1-1). If the sense pin detects a short between the thermocouple and the supply voltage or ground, the SCalert pin outputs a high voltage to the MCU (TC_SC MCU signal). Additionally, if the sense pin detects a lack of continuity in the thermocouple, the OCalert pin outputs a high voltage to the MCU. The Alert pins are user programmable and allow additional fault indication. Since there is no specific need for additional fault indication in this application, only one alert pin is connected to the MCU. The other three are left unconnected so as not to waste MCU GPIO. All alert outputs are push-pull active-high, so no pull-up resistors are required.

The MCP96L01 communicates with the MCU using the I2C protocol. The ADDR pin allows the application engineer to customize the slave address of the IC using an analog voltage. Since a single chip is used in this application, the ADDR pin is tied toground, which makes the I2C slave address of the chip 0xC0. In accordance with the I2C protocol, the clock signal is provided by the MCU to the SCL pin, and the data bus is attached to the SDA pin. 2kΩ pull-up resistors are used on the I2C lines, since the I2C protocol requires data to be transmitted using an open-drain/open-collector output configuration. The pull-up resistance was chosen based on logic level and switching speed considerations. The minimum resistance is determined by the maximum logic-low output of the MCU and MCP96L01. Too much current through the open-drain MOSFET can prevent the bus from being driven low enough to signal a 0 on the bus. For both the MCU and the MCP96L01 the maximum logic-low voltage is 0.4V at currents of 8mA (MCU datasheet pg. 235) and 3mA (MCP96L01 datasheet pg. 7) respectively. The minimum pull-up resistance is then computed as shown below:

$$R_{min} = \frac{V_{DD} - V_{OL}}{I_{OL}} = \frac{3.3\ \text{V} - 0.4\ \text{V}}{8\ \text{k}\Omega} = 362.5\ \Omega$$

The maximum resistance is determined by the speed of the serial communication. Larger pull-up resistors have larger RC time constants which slow the rise time, which can lead to signal integrity issues for large bus capacitances. For a preliminary capacitance estimate, a bus of length equal to half of the Rev 3 board with a width of 10 mil is considered. Fringing of the electric field at the edge of the PCB trace is ignored for simplicity. The calculation is shown below, using the geometry shown in Fig. 8.2. The dielectric constant of FR4 is taken from the JLCPCB capabilities web page.

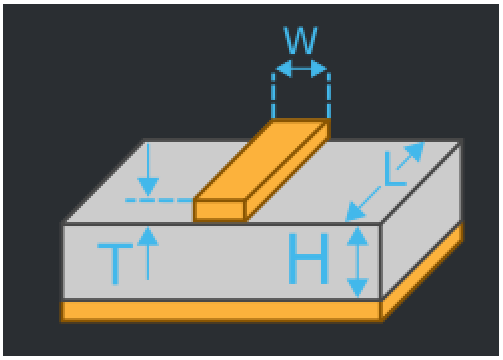


Figure 8.2. I2C Bus Capacitance Geometry

$$C_b = \frac{\varepsilon_r \varepsilon_0 W L}{H}$$

$$C_b = \frac{4.5(8.85 \times 10^{-12}\,\frac{\text{s}^4\text{A}^2}{\text{kg}\cdot\text{m}^3})(10)(0.0254 \times 10^{-3}\ \text{m})(5.5 \times 10^{-2}\ \text{m})}{1.6 \times 10^{-3}\ \text{m}/3}$$

$$C_b = 1.043\,\mathrm{pF}$$

Assuming that the MOSFET capacitances are negligible relative to the bus capacitance, the switching behavior of the I2C transceiver is approximated by a single time constant RC circuit. The bus voltage as a function of time after switching is given by the following:

$$V_b = V_{DD}e^{-t/RC_b}$$

Where R is the resistance of the pull-up resistor. The I2C specification requires that the rise time, defined as the time the bus takes to rise from 30% to 70% of the supply voltage, be less than 1µs for standard mode (300ns for fast mode). The rise time is then found from

$$0.7V_{DD} = V_{DD}e^{-t_1/RC_b}$$

$$t_1 = RC_b \ln(10/7)$$

$$0.3V_{DD} = V_{DD}e^{-t/RC_b}$$
$$t_2 = RC_b \ln(10/3)$$

$$t_r = t_2 - t_1 = 0.847RC_b$$

The maximum resistance for fast mode is then,

$$R_{max} = \frac{t_r}{0.847C_b} = \frac{300\,\mathrm{ns}}{0.847(1.043\,\mathrm{pF})} = 339.6\,\mathrm{k\Omega}$$

This is a relatively conservative estimate, so a value of 2kΩ should be fast enough for this application and will not prevent the I2C bus from being driven low. The specific value was chosen such that a resistor already in the design could be used.

9. IGNITION SYSTEM:

The ignition system is responsible for pushing at least 2A of current through the ignition ematch once the FIRE signal is asserted by the MCU. Additionally, the controller provides three continuity readings to provide the controller feedback on the ignition state of the engine. These ports are to be used to indicate ematch continuity, solid propellant continuity, and nozzle continuity. In order to supply 2A of current to the ematch using the low-power MCU signal, a power MOSFET is used to sink the ignition current. Since the 5V supply cannot supply 2A of current, the ematch current is drawn from the input voltage, which may be any voltage from 5V to 42V. For practical reasons, the assumed supply voltage is 12V since this is a reasonably low but common supply voltage. Since the supply voltage is somewhat arbitrary, a comparator is used to generate the e-match continuity signal. The ignition schematic is shown in Fig. 9.1, and the additional continuity schematics are shown in Fig. 9.2.

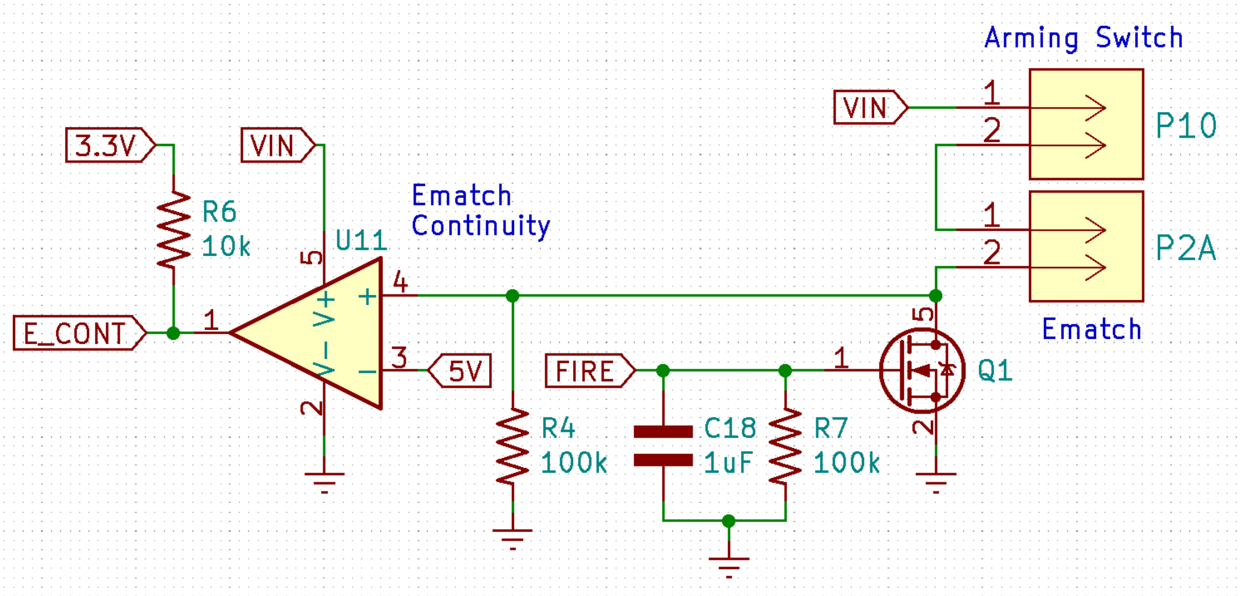


Figure 9.1 Ignition and E-Match Continuity Schematic

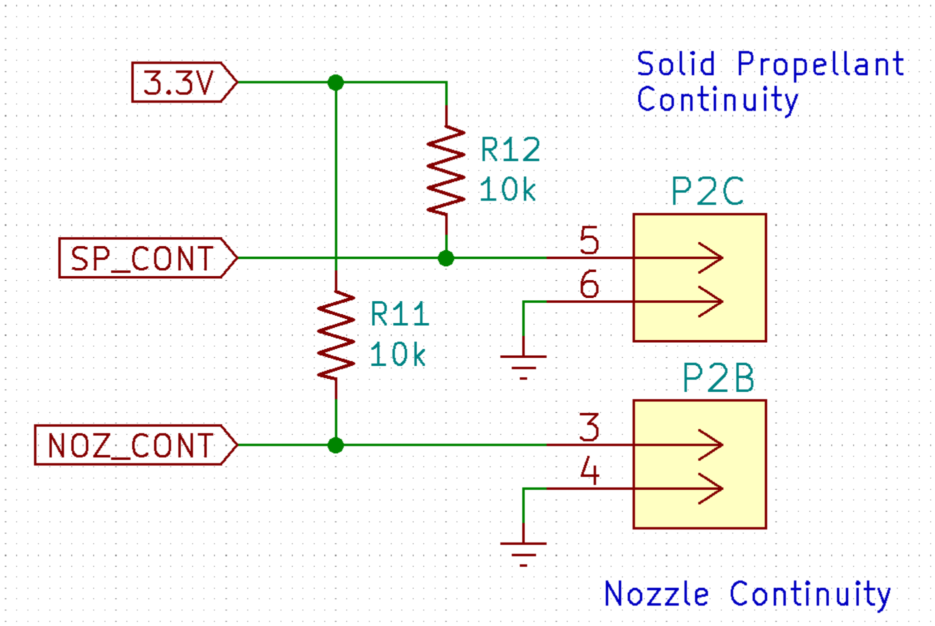


Figure 9.2. Continuity Wire Schematic

Power MOSFET:

The chosen MOSFET to drive the e-match current (Q1 in Fig. 9.1) has a maximum continuous current rating of 2A and a maximum pulsed current rating of 8A. Therefore, this MOSFET should be capable of providing the needed current for the short duration of time needed to ignite the e-match. The MOSFET has a maximum drain-to-source voltage of 30V, which ensures that the e-match can be used with input voltages up to 30V. To demonstrate the capacity of the MOSFET to supply sufficient current when a 3.3V signal is applied to the gate by the MCU, the current-voltage characteristic of the MOSFET is shown in Fig. 9.3

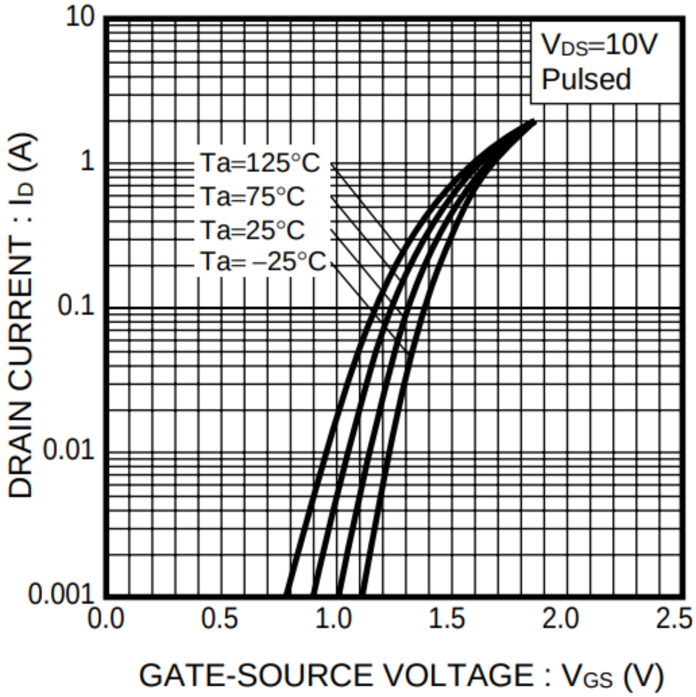


Figure 9.3. Power MOSFET Current-Voltage Characteristic (Datasheet pg. 3)

In Fig. 9.3. it can be seen that when 2.0V is applied to the MOSFET gate 2 amps are sourced when the drain-to-source voltage is 10V. Therefore, a 2 amp current surge through the e-match when 3.3V is applied to the MOSFET gate is reasonable.

It can be seen in Fig. 9.1. that a 100kΩ resistor and 1μF capacitor are also connected to the MOSFET gate. These components are used to prevent the MOSFET from igniting the e-match without a push-pull input from the MCU. The resistor pulls the gate to ground in order to prevent a floating gate triggering the e-match, and the capacitor prevents high-frequency noise or surges from triggering the e-match.

Continuity Wires:

As shown in Fig. 9.2, the connectors P2B and P2C allow a continuity wire to be run through the engine to provide feedback to the controller on the combustion status. The “solid propellant continuity” port is to be used with a wire running through the solid propellant in the combustion chamber such that the wire continuity is disrupted once the solid propellant is burnt by the e-match. The “nozzle continuity” port is to be used with a wire run across the exit of the combustion chamber nozzle such that the wire continuity is disrupted when hot exhaust is expelled out of the nozzle. Before continuity is broken during ignition, the continuity wires connect the MCU pins to ground. Once the connection is severed, the 10kΩ pull-up resistors pull the MCU pin to 3.3V. Thus, a high digital input at the MCU indicates a lack of continuity.

Comparator:

Since the input voltage powering the board may vary from 30V to 5V, continuity in the e-match is detected with the use of a comparator instead of a pull-up resistor. The comparator configuration is shown by U11 in Fig. 9.1. When the e-match is connected to the terminals of P2A, the non-inverting input of the comparator is connected to the input voltage. The inverting voltage is connected to the output of the 5V supply, which ensures that the comparator only indicates that the non-inverting input is greater than the inverting input when there is continuity in the e-match terminals. A 100kΩ pull-down resistor ensures that the non-inverting input is never left floating in order to prevent static charge on the screw-terminal from triggering the continuity indication. The chosen comparator uses an open-collector output, which allows the comparator to output a 3.3V signal while being powered from the board input voltage. The 10kΩ resistor on the comparator output pulls the continuity MCU pin to 3.3V when there is no continuity in the e-match. The pull-up resistance choice was made arbitrarily, and to match other resistors on the board.

10. LAYOUT CONSIDERATIONS:

11. REVISION HISTORY:

11.1 Revision 1.0

- Initial revision, never fabricated and tested.
- Contained microcontroller, pin headers, power supply, programmer, SD Card, and external flash.
- Used STM32L443VCT6 ARM Cortex-M4 microcontroller.

11.2 Revision 2.0

- Added 5V power multiplexer to automatically choose between USB and pin header power supply sources.

- Added schottky diodes to the input power supply trace to allow power to be supplied both through the 12V barrel jack and pin headers by shorting the two sources together.
- Improved buck converter traces.

Known Issues:

- Buck converter feedback path is incorrect

11.3 Revision 3.0

- Improved readability of 0603 silkscreen designators
- Fixed issues with feedback path of buck converter
- Swapped bulk decoupling capacitor for buck converter with smaller surface mount capacitor
- Switched microcontroller to M7
- Added mounting holes
- Added ignition interface
- Added LED indication to input and 5V rails
- Added USB Data traces and UART to USB converter
- Changed SWD programmer connector from 10 pin SWD to 20 pin standard JTAG connector
- Added traces for SWO and NRST to programming connector

Known Issues:

- Pinout of ignition MOSFET is incorrect
- SWD programming pin header pinout is incorrect, no MCU VDD connection is provided

11.4 Revision 4.0

- Replaced firmware status LED with RGB LED
- Removed prototyping pin headers
- Removed GPIO buffer chip
- Replaced IDC programming connector with a smaller connector to reduce form factor
- Changed buck converter input and output ceramic capacitances
- Added pull-up resistors to the SWD lines

- Changed USB transceiver pull-up/pull-down resistances
- Added PT amplifier
- Added PT multiplexing and connectors