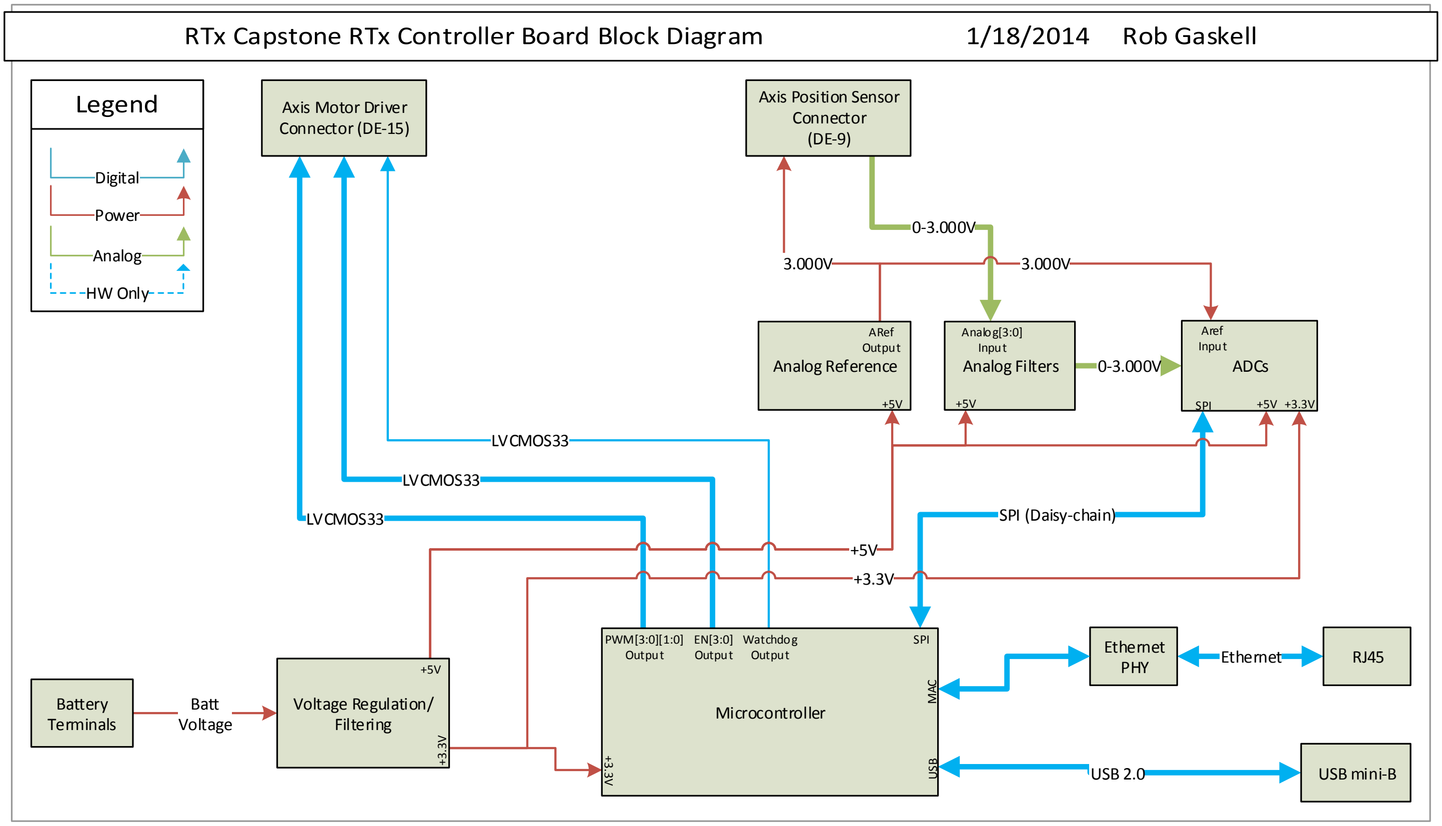
RTx Controller Board Design Document

RocketTracks Capstone 2014

The RocketTracks Controller board controls the position of the axes on the RocketTracks camera and antenna pointer. The RTx Controller Board features an Ethernet port for communication with input control devices, as well as a USB port to aid in firmware development and debugging. Commands and tracking data will be sent via Ethernet to the RTx Controller board, and the onboard microcontroller will process the data and output PWM and other control signals to the Generic Motor Driver boards for each axis.



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I. Axis Position Feedback

A. Axis Position Feedback Overview

RocketTracks uses a potentiometer as a position sensor for each axis. The output voltage is filtered and compared to the input reference voltage via an on-board ADC. The Low-Pass Filter is designed based on control theory requirements, and is a compromise of noise-reduction and phase margin requirements.

B. Analog-to-Digital Converters (ADCs) for Feedback circuits

1. Component List

a) ADC1

C1	C4	C5	ADC1

b) ADC2

C2	C6	C7	ADC2

c) ADC3

C3	C8	C9	R16	ADC3

d) ADC4

C40	C41	C42	R20	ADC4

e) Analog Reference Voltage Regulator

C23	C24	C25	REF1

2. Design Overview

a) ADC Resolution

The resolution of the axis position feedback ADC's corresponds to the resolution of measurement of the angular position of the axis. Assuming the potentiometer provides a resistance through the axis range of motion which is linear with angle and corresponds to a full-range output voltage sweep through a 360-degree rotation, we have:

$$Resolution_{\theta} = \frac{360^{o}}{2^{Resolution_{ADC}}} \Rightarrow Resolution_{ADC} = \log_2 \frac{2\pi\, rad}{Resolution_{\theta}}$$

The tracking precision required at full-range is then:

$$Resolution_{Range} = Sin(Resolution_{\theta}) * Range$$

$$\Rightarrow Resolution_{\theta} = \arcsin\left(\frac{Resolution_{Range}}{Range}\right)$$

$$\Rightarrow Resolution_{ADC} = \log_2 \frac{2\pi\, rad}{\arcsin\left(\frac{Resolution_{Range}}{Range}\right)}$$

We must track a ~2m length object at distances in excess of 18,000ft. However, we need not stay perfectly centered on the rocket at this distance, as video will not be at full zoom, and telemetry signals require less precision than video. Assuming we want to keep the rocket both in the frame and zoom such that the rocket length is 5% of the frame, the tracking resolution at this range becomes:

$$Resolution_{Range} = \frac{2m}{10\%} = 20m$$

$$Resolution_{ADC} = \log_2\left(\frac{2\pi\, rad}{\arcsin\left(\frac{20m}{5500m}\right)}\right) = 11bits$$

However, the control system will not be capable of tracking to 1 LSb of the ADC, so as a rule of thumb we will assume tracking precision to within 30% of ADC resolution. Then we have:

$$Resolution_{ADC} = 11bits + 30\% * 11bits = 15\ bits$$

As ADC's are most commonly available in power-of-2 resolutions, a 16 bit ADC will be used.

b) ADC Digital Interface

Given a sample rate of 2000Hz as described in section B.3.a below, we must have a data bandwidth of 2kSamples/sec, with a sample size of 16 bits or 2 Bytes. We must then have a data bandwidth of 4kB/s for each ADC, or 16kB/s if they are on a shared or daisy-chained bus. However, latency is of great concern in a control system, so it is not sufficient that the data transfer complete within the sample period.

A daisy-chain SPI interface allows a single sample command to be issued to all ADC's simultaneously, and allows a single data transfer from all axes to be performed with lower overhead as compared to a chip-select based SPI interface.

c) ADC and Analog Reference Voltage Regulator Choice

Common ADC data buses are I2C and SPI. The AD7685 is a 16-bit ADC supporting both SPI and daisy-chain serial interfaces at up to 55MHz, or more than 6.5MB/s. It also has a sample rate of up to 250kSamples/s, and a sample-to-data ready time of no more than 2.2us, minimizing latency and satisfying throughput requirements.

(1) ADC Supply Voltages

The AD7685 has separate supplies for the converter and for the digital I/O interface. V_{IO} was chosen to match that of the microcontroller, while V_{DD} selection was based on the desire to minimize conversion latency, as higher voltages allow for faster conversion times as well as higher conversion rates. The following voltages were chosen:

$$V_{IO} = 3.3V$$

$$V_{DD} = 5V$$

(2) Reference Voltage Regulator Choice

A stable and noise-free reference voltage is required for the ADC and feedback position sensor potentiometer circuits. The chosen analog reference voltage regulator is recommended for use with the AD7685, and is offered in a range from $2.048V\ to\ 5.000V$. The $5.000V$ model, ADR435, was chosen as the higher voltage maximizes the signal-to-noise ratio.

(3) ADC Decoupling Capacitors

Per the datasheet, 0.1uF capacitors were chosen to decouple the supply pins. A 1206-package 22uF capacitor with an X5R temperature coefficient decouples the analog reference input pin, as this is the recommended value when using an ADR43x reference voltage regulator.

(4) Analog Reference Supply Decoupling Capacitors

The ARef regulator's supply pin is decoupled with a 10uF and 0.1uF capacitor, and the output is decoupled with a 0.1uF capacitor, per the device datasheet.

3. Summary of Parameters

$Resolution_{5500m} = 20m$

$Resolution_{ADC} = 16\ bits$

$V_{aref} = 5.000V$

$V_{DD,ADC} = 5V$

$V_{DD,aref} = ?\,V$

$V_{IO,ADC} = 3.3V$

C. Low-Pass Filters for Feedback ADCs

1. Component List

a) *ADC1 Feedback LPF*

R1	R2	R3	C10	C11	C12	C13	OPAMP1-A

b) *ADC2 Feedback LPF*

R4	R5	R6	C14	C15	C16	C17	OPAMP1-B

c) *ADC3 Feedback LPF*

R7	R8	R9	C18	C19	C20	C21	OPAMP2-A

d) *ADC4 Feedback LPF*

R17	R18	R19	C36	C37	C38	C39	OPAMP2-B

2. Design Overview/Component Choice

a) Control Bandwidth and Cutoff Frequency

The control bandwidth frequency f_{CBW} for the closed-loop control system was chosen based on the requirement to track fast-moving objects with video during manual and automated control operation. The cutoff frequency f_C for the ADC input LPF is specified to be one decade higher than f_{CBW}. This convention places f_C far enough above the f_{CBW} to prevent the LPF from limiting performance at the f_{CBW}, while still providing satisfactory noise filtering.

$$f_{CBW} = 2.5Hz$$

$$f_C = 2.5Hz * 10 = 25Hz$$

b) ADC 1-bit Frequency, desired noise level and Filter Order

The frequency of the ADC's LSB f_{1bit} is the minimum frequency at which we will observe a change on the least significant bit. The maximum noise level desired at f_{1bit} is -96dβ. f_{1bit} must be a low enough frequency such that the Nyquist rate is reasonable given our choice of ADC's and microcontroller. With a 3rd Order LPF with our $f_C = 25Hz$, we have:

$$f_{-96d\beta} = 995Hz$$

The Nyquist rate, or minimum rate we must sample the ADC's is then $995Hz * 2 = 1090Hz$, which is a reasonable sample rate for the system.

c) Topology

A Sallen-Key topology Butterworth Low-Pass Filter was chosen due to its simplicity, and the ability to attain 3rd-order filtering and a low f_C with relatively low RLC values in combination.

d) Op-Amp

The AD861x Op-Amp was chosen to produce the Sallen-Key topology because it is recommended for use in conjunction with the chosen ADC's.

3. Consequences

a) Control Rate and ADC Sampling

A rule of thumb for minimum control rate is $f_{CR} \geq f_{CBW} * 40$, then:

$$f_{CR} \geq 2.5Hz * 40 \geq 100Hz$$

The Nyquist rate must also be satisfied, so the sample rate must be:

$$f_S \geq 1080Hz$$

Choosing $f_{CR} = 100Hz$ and $f_S = 2000Hz$ gives us 20 samples per control loop iteration.

4. Summary of Parameters

$f_{CBW} = 2.5Hz$

$f_C = 25Hz$

$f_S = 2000Hz$

$f_{CR} = 100Hz$

II. Microcontroller

A. Microcontroller Overview

The RocketTracks Controller must process axis feedback position data as well as desired position data from the manual controller and target position data from the Sightline device, both of which communicate via Ethernet. It must also drive the PWM and control signals required by the PSAS Generic Motor Driver boards. The STM32F407 was chosen for its support of Ethernet, SPI for receiving axis postion data from the ADC's, plentiful PWM output capabilities, as well as its current use with other PSAS projects and its support of ChibiOS/RT, the operating system used by other PSAS projects.

B. Microcontroller circuit

1. Component List

R36	R38	R168	C78	C79	C80	C81	C82	C83	C84	C85
C86	C87	C88	C89	C90	C91	C92	SW1	J22	U1	

2. Design Overview/Component Choice

a) Peripheral Requirements

(1) Ethernet MAC

The 10/100 MAC peripheral meets the requirements for bidirectional communication with the RTx Manual Control Box as well as the Sightline device.

(2) SPI Controller

The ADC's described in section I when used in Daisy-Chain mode require a minimum digital interface clock period of 18ns with the 3.3V IO voltage used. The maximum digital data bus frequency then is:

$$f_{SPI,max} = \frac{1}{18ns} = 55.6MHz$$

The STM32F407's SPI1 Controller has a maximum frequency of 37.5MHz, so the SPI controller can run at a high frequency without risk of violating the timing requirements of the ADC's. With 4 16-bit ADC's sampling at 2kHz, as described in section I, the minimum bit rate is then:

$$f_{SPI,min} = 2kHz * 4 * 16bits = 128kHz$$

So, the 37.5MHz bit rate is sufficient and will provide relatively low latency.

(3) PWM

Each axis requires a pair of PWM signals with independent single-edge control. This means a total of 8 PWM outputs to support up to 4 axes. The STM32 easily accommodates this requirement, with several of its hardware timers supporting 4 PWM channels each.

(4) External Interrupts (EXT)

The ADC's are interfaced to the microcontroller using a Daisy-Chain configuration with a busy indicator. In this mode, the ADC nearest the microcontroller in the chain drives its SDO line high when the data is ready. This signal can be used to interrupt the microcontroller and initiate the data transfer using the SPI controller. The STM32F407 supports external interrupts on most of its GPIO pins, allowing use of this feature.

(5) GPIO

Additional digital outputs are required to operate the PSAS GMD's. Each GMD requires an Enable signal as well as a Watchdog signal which switches periodically, so an additional 8 GPIO pins are required. The STM32F407 chosen has 114 GPIO's, far surpassing this GPIO requirement.

(6) Analog-to-Digital Converter

As axis position is considered safety-critical data, it was deemed necessary to monitor the Analog Voltage Reference Regulator to ensure accurate operation of the axis position sensor ADC's. The STM32F407 has multiple internal ADC's which are multiplexed on multiple channels and GPIO pins.

(7) Multiplexing of Pins

In addition to supporting each peripheral, all peripherals must be accessible to external devices with which they communicate. While it is possible to multiplex pins at runtime for use with more than one peripheral, this adds complexity and latency to firmware, as well as to external hardware. The 100-pin version of the STM32F407 allows independent GPIO interfacing with all required peripherals as well as those described in the following Program, Debug and Development Support subsection.

b) Program, Debug and Development Support

(1) Programming and Debug

The STM32F407 supports both JTAG and SWD for programming and on-chip debugging. A standard JTAG/SWD header was used which is common to other PSAS projects.

(2) Development Support

A USB port was added to the RTx Controller for development support only. Chibios/RT features a command-line shell that is easily connected via USB, and is a convenient way to communicate with the STM32F407 for development purposes.

c) Supply, Digital IO and Analog Voltages

III. Ethernet Port

A. Ethernet Overview

RocketTracks uses the Ethernet protocol to receive command and tracking data to be used by the microcontroller for processing. The microcontroller has an onboard 10/100 Ethernet MAC which is interfaced to an external Ethernet PHY. The Ethernet PHY has a connector with built in magnetics for proper signal integrity. An additional power over Ethernet (PoE) controller maintains appropriate power levels to be supplied over the Ethernet interface.

B. Ethernet PHY

1. Component List

U3	R56	R55	C73	C75	L3	C97	C98	C76	C77	R60	C99	C54

2. Design Overview

Micrel's KSZ8081RNAIA was chosen as the Ethernet transceiver for its compact design and ability to easily communicate with the chosen microcontroller. In addition, the timing control for the KSZ8081RNAIA can be done from the MCO output of the microcontroller and even generate the necessary 50MHz reference clock to be sent back for use with the RMII mode of operation. The component operates from a single 3.3VDC power supply.

The capacitors and inductor are all recommendations by the manufacturer to ensure proper data transmission and reception. Bypass capacitors are placed close to the device itself to ensure proper supply voltage levels during operation and signal integrity.

The Ethernet transceiver also requires a clocked input either from a separate external oscillator or from a clock signal coming from the microcontroller. Since the microcontroller has the ability to provide a clock signal to the transceiver, adding a separate crystal oscillator seemed redundant. There are also sufficient GPIO pins to support this. Therefore the microcontroller will supply the Ethernet transceiver with its clock input.

3. Summary of Parameters

The RMII interface is used to communicate with the microcontroller.

A 25MHz clock signal is required from the microcontroller to synchronize timing of data transmission and processing. This will be sourced from the microcontroller. A 50MHz clock will be generated by the KSZ8081RNAIA to be sent back to the microcontroller for proper RMII synchronization.

C. Ethernet Connector

1. Component List

X8	R59

2. Design Overview/Component Choice

The Ethernet protocol requires signal isolation through transformer coupling. This can be achieved from a dedicated LAN Discrete Transformer Module or from an Ethernet connector with incorporated transformers. A connector with incorporated transformers was chosen to reduce needed board space and improve signal reliability. The connector transformers also support center-tapping, which is used on the controller board to supply PoE. Built in LEDs allow for visual Ethernet diagnosis at the connector itself.

D. Power over Ethernet (PoE)

1. Component List

IC2	C50	C48	L2	R_LED	C44	D4	C51	R99	D5	R24	R23

2. Design Overview

Maxim's MAX5984C was chosen in order to incorporate PoE to the RTx design. The component is a single PSE controller compliant with IEEE 802.3af/at standard. This model allows for PoE+ which will offer an output power tolerance of up to 40W; sufficient to source power to the external devices requiring power from Ethernet.

The PoE controller circuit was taken directly from the product datasheet when used from a single 48VDC supply and incorporated with indicator LED for diagnostic purposes.

IV. USB Development/Debug Port

A. Component List

R21	R22	C45	C46	U2	X4

B. Design Overview/Component Choice

The USB port requires ESD protection. For this TI's TPD4S012 was chosen because it was a cheap and straightforward solution. A 22Ω current-limiting resistor was placed in series on the D+ and D- line. The two capacitors were placed to reduce noise. The capacitor and resistor sizes were the suggested sizes on the datasheet for the TPD4S012. The pins selected on the microcontroller were chosen to be the same as those used for USB on the dev board. Note: the TPD4S012 was removed from the design due to PCB layout complications.

V. Supply Voltage Regulation/Filtering

Device	Input Voltage (V)		Output Voltage (V)			Output Current (mA)	
	Min	Max	Min	Typ	Max	Min	Max
TLE4476D	4.5	42.0	3.17	3.3	3.43	350.0	900.0
TLE4476D	5.7	42.0	4.8	5.0	5.2	430.0	900.0
ADR435RM-8	7.0	18.0	4.998	5.000	5.002	-20.0	30.0
TL751M08QKVURQ1	9.0	26.0	7.76	8.00	8.24	5.0	75.0
LMZ14202HTZ	6.0	42.0	5.0	-	30.0	2400.0	3950.0
CHB75W-24S48-C	9.0	36.0	47.5	48.0	48.5	0.0	1560.0

Since the ADR435RM-8 power supply will be used for precision analog reference, it was desired that an LDO power supply be used as its input voltage source instead of the switching power supply, used to drive other components. The TL751M08QKVURQ1 was chosen to act as this filter between the switching and analog reference power supplies. The TL751M08QKVURQ1 allowed for a 12V input from the LMZ14202HTZ with an output close to that of the minimum voltage for the ADR435RM-8. Using the minimum input voltage for the ADR435RM-8 meant that less power loss would occur through this component. The TL751M08QKVURQ1 was chosen as a robust component, as it is cataloged for use in automotive applications, at a broad range of ambient temperatures, with very low dropout voltage (less than 0.6V) when used at high current. The component is also surface mount, requiring minimal board area, and with a standard type package already found in the present device library.

VI. Motor Driver Outputs