Project Definition

The objective of this project is to develop a direct-drivable, low-cost, educational 2R robot arm capable of continuous rotation. Additionally, the robot must have the following characteristics:

- Easily programmable and transparent at all levels (microcontroller to high-level).
- Intuitive user interface for college students.
- Table-top size (linear height ~0.5m); portable
- Easy to configure horizontally or vertically and adjustable for multiple configurations of the arm (2 motors, either motor removed, etc)
- Easily serviceable electromechanical system
- Easily programmable to different control modes (position, force, hybrid, etc)

Sponsor Needs

Our sponsor, Professor Kevin Lynch, provided the team with the following technical requirements for the robot:

- Two BLDC motors at the base, with one connected to the second joint by a timing belt. Each link has load-mounting points so that users can change the center of mass and inertia of the link.
- Either motor can be removed to make an under actuated robot, e.g., an inverted pendulum (2nd motor removed) or a "pendubot" (1st motor removed).
- Each motor can have no gearing ("direct drive") or gearing (~10:1).
- Each motor has a high-resolution encoder. May use a homing procedure for the robot if necessary.
- A small control box that houses the amplifiers, power supply, microcontroller, etc., with a USB connection to a laptop, 120V to wall, and cables to motors and encoders.
- Current (torque) sensing and control.
- Easy table mount to allow operation in vertical or horizontal orientation.
- Sufficient torque for the motors to continuously hold unloaded outstretched arm against at least 2x gravity.
- Removable mechanical stops for joint limits or continuous rotation.
- Easy control law and filter development and downloading to the microcontroller.
- Interface with MATLAB or Simulink on laptop, with easy visualization of controlled trajectories.
- Simple move functions from the MATLAB interface (e.g., step motions, polynomial trajectories, etc.,) that allow easy testing of the control laws.
- Robust design capable of withstanding years of repeated use in a classroom setting (by freshmen)

Electrical Analysis

The engineering specifications for the electrical system were dictated by the needs of both the software and mechanical teams. As a result, the specifications as designed in the final fabrication documentation shall be provided with requirements-driven justification. Any tangential or independent design discussions will be presented as well. As a note: this section reflects the PCB implementations pre-damage and for future fabrications. While the breadboard implementation retains full functionality, its design specifications, either those lacking or secondary to the primary design, are not presented here.

Power Specifications:

1. Wide input voltage: 22VDC to 56VDC
    a. Selected to allow for a wide range of motors to be used
2. Fused 25ADC peak current draw
    a. Selected to allow for up to 11A per motor channel (See 4.a) and 2A for peripheral electronics
    b. Peripheral electronics allocation was generous to allow for future development should it be deemed necessary
3. Reverse polarity protection
    a. Common P-MOS/Zener circuit selected for simplicity
    b. Protects against improper student device handling
    c. “Tried and true” circuit implemented on thousands of commonly found devices worldwide
4. Over voltage protection
    a. Zener diode circuit to breakdown at (V_z = 56VDC) 56VDC to compensate for imperfect power supplies
    b. Protects against improper student handling of device
    c. Microcontroller monitors primary input rail to allow for motion control in the event of the motor’s regenerative effects increasing bus voltage
5. Multi-layer ESD protection
    a. Fast acting TVS diodes on output of 3.3V, 5V, and primary power rails to short all ESD and transient voltage spikes to ground
    b. Protects against ESD-related damage
6. 750W 24V (+/- 2V) Power Supply:
    a. To allow for simultaneous peal current draw by both motors (See 4.a)
    b. To compensate for non-ideal effects of devices causing voltage drops (24V scaled to 26.4V)
7. TI Simple Switcher 3.3V and 5.0V switching regulators
    a. Greater than 80% efficiency; far greater efficiency than linear drop-out regulators
    b. Low thermal footprint
    c. Ease-of-use, well documented
    d. Wide voltage input range (up to 60VDC)

Microcontroller Selection - TM4C1294NCPDT

1. Device requested by software with the following specifications highlighted
2. 120MHz operation
    a. Selected to allow for operating 1kHz control loop while interfacing with multiple sensors and performing data analysis.
3. Four SPI Buses
    a. One SPI bus per encoder to prevent any single encoder, should one fail, from preventing the other from failing; safety feature since encoders do not have a fault pin
    b. One SPI bus to interface with both motor controllers; permissible as both motor controllers have a separate fault pin in the event of a failure event.
    c. One SPI bus for RAM, should RAM be needed for any future complex programs
4. ADC inputs
    a. Eight ADC inputs available for use, two broken out for miscellaneous interface
    b. Other ADC lines used for current sensing, temperature sensing, and optional force sensing
5. Plentiful GPIO pins available
    a. Allowed for the interface of all devices, both those necessary for operation and those implemented for safety or future expansion
    b. Of the 90 available, less than 20 remain unused
6. Widely documented and well understood by peers
    a. Significant documentation available from Texas Instruments
    b. Organizational-wide use of device allowed for cross-team support

Encoder Selection – Renishaw Orbis (BR10SPC14B12CH00) Absolute Encoder

1. Brand
    a. Selected for its reliability, value, legacy within robotics, and corporate support via technical documents and warranty
2. 14-bit Resolution
    a. Selected as 14 bit yields 16384 steps; when selected, 'back of the envelope' calculations yielded the team required at least 12 bits, therefore, 14 bits provided room for error
3. SPI Interface
    a. Selected to interface with known TI libraries and large support for encoder SPI interface from Renishaw
    b. Low-noise environment allowed for this sort of interface to be selected
    c. SPI interface speed fast enough
4. Magnetic, non-contact
    a. Magnetic encoders are less prone to improper readings due to age, dirt, and other environmental conditions impacting optical encoders
    b. Non-contact encoder to prevent friction-related wear-and-tear on the device

5. Absolute
    a. Selected to prevent need for homing features and to allow for students using the device to know the position of the arm links at all times with precision.

Electrically Driven Motor Requirements

1. See mechanical for full motor selection discussion and motor specifications
2. Motor voltages were limited from 24V to 48V for safety and cost purposes
    a. US OSHA defines "high voltage" as voltages exceeding 50V and a 50V supply is necessary to drive 48V motors
3. Motor current limit was set at 10A per motor
    a. Selected to maintain PCB manufacturability and to prevent extreme PCB costs due to heavy weight copper

Motor Controllers – TI DRV8323R Three-Phase Smart Gate Driver

1. Large selection of MOSFETS available for use
    a. Motor Driver capable of sourcing 1A and sinking 2A to drive MOSFETS
2. Wide voltage range: 6 to 60VDC
    a. Wider operation than the electronics' specifications of 22 to 48VDC
3. Three integrated current sense amplifiers for monitoring to allow for coil winding current monitoring
    a. Adjustable gain and bidirectional capabilities
4. SPI-based device
    a. Selected over GPIO control to allow access to a richer set of control features
5. Multiple commutation methods available, two of three methods accessible to user with given design to allow students to learn about multiple control modes and for the implementation of both simple and complex controllers
    a. PWM 1x – trapezoidal commutation; motor controller performs commutation onboard and microcontroller provides direction and speed via a GIPO and PWM signal, respectively
    b. PWM 3x – sinusoidal commutation; microcontroller performs commutation and provides three PWM signals and a direction signal to command motor
6. Widely documented and well understood by peers
    a. Significant documentation available from Texas Instruments
    b. Organizational-wide use of device allowed for cross-team support

UART Communications – FTDI FT230X

1. FTDI UART-to-USB branded devices were selected due to significant, open-sourced documentation and industry-wide legacy
2. Extra header broken out to bypass FTDI chip in the event of device failure or the need for a different, non-USB device to communicate with the electronics; allows for future expansion

Other Peripherals

Note: Justification for some electronics is not provided, as devices are included for "proof of concept" as they were not included in system requirements. This is indicated clearly in the discussion for each of such devices.

1. Temperature – Analog K-Type thermocouples to monitor motor temperature
    a. Selected for ease of implementation and wide variety of open-source, well-documented circuit designs
    b. Selected for wide temperature range and rapid response time

2. ESTOP
    a. Both motor drivers may be disabled via a software stop command or an external ESTOP button.
    b. Implemented with via an AND gate that joins the software and hardware commands; selected as discrete gates are more robust and have lower latency than other interfaces
    c. LED active when system active, LED off when system disengaged, following known practice
3. JTAG Programming Interface
    a. Selected over SWO for legacy and class-wide familiarity
    b. JTAG interface broken out to side of electronics box to allow students to easily reprogram the microcontroller
4. Force Sensor
    a. If needed, analog input for TE Connectivity FC22**,** with header installed, available for future expansion
    b. See schematics and software documentation for further details. Device not included, external wiring not installed.
5. IMU
    a. If needed, I2C-based 9DOF (triple axis acceleration, rotation, and magnetic sensing) SparkFun Electronics MPU6050 with header installed available for future expansion
    b. See schematics and software documentation for further details. Device not included, external wiring not installed.
6. RAM
    a. If needed, SPI-based interface for 4MB Fujitsu MB85AS5MY available for future expansion; see schematics and software documentation for further details.
    b. RAM IC not populated on PCB, support hardware populated

Electrical Design Evolution

There were few major electrical changes between initial inception and the delivered design. The microcontroller, encoders, temperature sensors, and input power electronics remained unchanged from their selection early in the winter quarter. The voltage regulators selected changed from low-voltage input to wide, high-voltage input regulators to allow for a wide variety of motors to be used with this design. The family of regulators, the TI Simple Switchers, remained in place throughout the project. The motor drivers selected early in the first quarter were improperly spec-ed due to a misunderstanding in the motor selection process. The motors selected after resolving this error required higher-powered drivers, leading to the selection of the TI DRV83xx series of motor drivers. Two modes of operation were requested by the client, so, both modes were made accessible via 0.1” headers and jumpers.

The requirements for including a force sensor and an IMU were dropped during the course of this project. The support circuitry for these devices remained in the final designs as an optional, but untested, feature for future expansion. The requirement for the use of bulkheads, or panel mounted connectors, was added half way through the spring quarter. This was a simple requirement to meet that further complimented the existing electronic design.

Finally, after the PCBs were fabricated and tested, a series of tests indicated the need for a few changes. A detailed description of these changes is included in the electrical final design description. However, the high-level changes included:

- Correcting the PCB footprints for the RAM and crystal
- A 180-degree rotation of three improperly placed diodes
- Removal of a short that tied the microcontroller’s core voltage bus to ground
- Implementation of basic ESD protection on the primary input, 5V, and 3.3V voltage buses
- Improved UART-to-USB circuity and an optional UART breakout for USB device bypass
- Modification of the motion controller to allow for proper trapezoidal (PWM 1x) and sinusoidal (PWM 3x) control modes
- The “tenting” of all vias and the addition of a conformal coating to provide electronics with environmental, ESD, and arc flash protections

Electrical Design

Changes from First Board to Second

The majority of the preproduction prototype electronics system functioned as designed. There were a few changes implemented either on the final PCB, the final design documents only, or both. The list of changes are as follows:

On the PCB and Documented:

Note: All device designators reference the prototype hardware. Final device designators may be found by comparing the first production schematics with the final production schematics.

1) The microcontroller's core voltage regulator was accidentally shorted to ground instead of being shorted to another core regulator pin. On the prototype hardware, the ground line was cut and the shorted pin (114) was white wired to the proper pin (87) on the microcontroller. On the final designs, the proper routing was implemented.
2) The FTDI chip (UART to USB interface) was deemed non-functional on the present PCB. The reasoning for this is unknown as FTDI's datasheets were ambiguous. This chip was bypassed and a drop in SparkFun-branded FTDI-to-USB adaptor was used with success. To implement the aforementioned, resistors R1, R3, R9, and R11 were removed to interface the FTDI chip with existing hardware. On the final designs, the open-source FTDI designs used by SparkFun were copied nearly identically to properly implement the FTDI device.
3) The Zener diodes on the 3.3V (D14) and 5V (D12) regulator outputs were wired backwards in the schematic. These devices were flipped on existing hardware to realize 3.3V and 5V rail functionality. The devices were placed with proper directionality on the final documentation.
4) The RAM footprint on existing hardware was deemed too small for the IC. The RAM was deemed unnecessary for present operation, so, it is not populated on existing hardware. Final documentation includes the proper footprint should future revisions of the board require RAM.
5) The input TVS diode, D10, was rated for 6V instead of 60V. This diode was removed on the prototype hardware. On the final design, the device was replaced with a Zener diode with a Zener voltage of 56V.
6) The crystal, Y1, on the protype hardware used an incorrect footprint. To allay this issue, the crystal was removed on the prototype. In the final documentation, the incorrect footprint was replaced with the correct footprint.
7) The motor winding current sensor measurements were deemed too noisy for processing. DSP techniques were deemed too computationally complex and/or intensive for realization on the prototype hardware. An RC filter was placed on the output of both U12 devices (pin 8) to filter some of the noise. In the final documentation, RC filters were placed on each of the three outputs of the motor controller's current sense amplifiers.

Only in Documentation:

1) Extra TVS diodes were placed on the output of the 3.3V and 5V rails to enhance ESD protection for the circuit.
2) An improved TVS diode was placed on the primary voltage input to provide further ESD protection.
3) A UART breakout header was realized to allow for a user to bypass the onboard FTDI device to allow for quick repairs should the FTDI device fail. This header also allows for the use of other UART devices (e.g. Bluetooth to UART) in conjunction with this design. Four zero-ohm resistors must be removed to allow for this header's proper functionality.
4) The primary input power connector was flipped 180 degrees to allow for the MOLEX connector to lock into place. On the prototype design, the connector does not lock completely as the connector is located too close to the fuse holder.

Electronics Fabrication and Assembly

To assemble the PCB, send the ZIP FILE to any reputable PCB fabrication company. It is recommended that complete assembly be purchased.
To assemble non-PCB electronics, purchase all items listed on the "NON-PCB BOM" and follow the instructions listed in the cable harnessing documentation. Complete electronics box assembly requires review of both cable harnessing documentation and the electronics housing documentation.

Test Bench Discussion

Unfortunately, an accident near the end of the second quarter resulted in both corrected but improperly designed PCBs to be deemed irreparable and unsafe. As a result, a breadboard realization of the system was used for demonstration purposes. Significant engineering analysis indicates the inevitability of some of the errors contributing to the untimely demise of all fabricated PCBs. Other contributing factors included untidy electrical workbenches and statistical variation in component lifetimes (e.g. MTBFs). The team performed all possible repairs up and until informed to cease fabricated PCB repairs at the judgement of the electrical design lead and the project's sponsors.

Electrical: Benchtop

Motors + SPI Device

1) Build power supply AC and DC cable bundles. Check the AC input voltage and DC output voltage. Adjust supply voltage to 24.5VDC.
2) De-energize all power systems.
3) Populate R36, R37, and R38 with 0-ohm resistors (or solder) as device is to be used in PWM -1x mode.
4) Connect motor controller to development board.
5) Clamp motor to table, gently
    a. Enough force to hold the motor stable, but not so much to damage it.
6) Connect motor-to-motor controller.
7) Connect motor halls to motor controller
8) Connect development board to computer

9) Connect power to motor controller.
10) Energize system and check for error indicators
    a. If error indicator, follow datasheet.
11) Assist software team in debugging and setting up interface software.
    a. Since the controller uses SPI, this test also certifies the functionality of the SPI bus.
12) Test motor's motion:
    a. ¼ peak current
    b. ½ peak current
    c. Peak current
    d. Spin motor forward and backwards
    e. Test motor holding position
    f. Test simple speed control using halls only

Encoders

1) Build encoder test rig with mechanical team. In this phase, follow RLS guidelines to ensure the encoder read head and magnetic ring are aligned with proper tolerances
2) Connect wires to encoder board to interface encoder to microcontroller. Label each wire for software to interface.
3) Before mounting encoder on test rig, power on the encoder and follow RLS guidelines to ensure proper power up occurs.
    a. Typically, a success indicator is an LED with a specific flash pattern.
    b. If the encoder does not pass this test, call RLS. The device may be defective.
4) Mount the encoder on the mechanical rig. Power on the encoder. To check alignment, check the RLS guidelines. Disconnect power upon completion.
    a. Typically, a success indicator is an LED with a specific flash pattern. This pattern will differ from the power on success pattern.
    b. If the encoder does not pass this test, work with mechanical to resolve tolerance issues.
5) Connect encoder to microcontroller's SPI bus for software team. Allow software team to test encoder interface.
6) Test encoder spinning forward:
    a. ¼ turn
    b. ½ turn
    c. Full turn
    d. Test velocity (spin ring freely and observe data, does it start fast and slow down?)
    e. Check position: does the encoder
7) Repeat 6 (a) through (e) for backward spins.

I2C Device

1) Solder leads onto the I2C device breakout board
2) Connect device to microcontroller not forgetting SDA/SCL pull up resistors.

3) Assist software in communication protocols
4) IMU: move IMU in 3D space and ensure data is logical.
    a. Rigorous testing of this sensor is unnecessary as it could be dropped from the design.

Analog Device (Temperature Probe)

1) Using the software team's ADC code, perform a 0V to 3.3V sweep. Review all data for errors or noise.
2) Note analog noise and propose methods to fix, if necessary.
3) Setup the temperature probe breakout board according to the datasheet. This should involve soldering headers to the board and applying 3.3V power.
4) Strip a K-Type thermocouple for use by the probe.
5) Connect the sensor to the microcontroller.
6) Using the ADC code, test the thermocouple with a series of different temperature objects (ICE, human, laptop, room temp). Convert raw values using the formula found in the data sheet.

Electrical: PCB

The following describes the methods of testing the critical electronic subsystems. All other electronic subsystems have built-in testing procedures that will alert the user to system failures.

Input power:

a. Insert 25A fuse into F1 fuse holder
b. Locate a power source of at least 22VDC, capable of sourcing at least 22A
c. Attach to this power supply a 6-pin MOLEX MiniFit Jr female housing. Polarity of the pins are as follows: 1-3 positive, 4-6 negative
d. Ensure power supply is deenergized
e. Attach MOLEX connector to P8.
f. Energize power supply
g. Observe
    i. D11: Is it on? If not, stop. The main power input has failed
    ii. D17: If not on, 3.3V has failed
    iii. D14: If not, 5V has failed.
    iv. If all are on, power regulation is functioning as planned. To be certain
        1. Probe TP6 and ensure this value is nearly 5V with low ripple
        2. Probe TP7 and ensure this value is nearly 3.3V with low ripple
    v. **If these tests fail, do not proceed to test any further. This is a critical failure and a dangerous situation.** Debug power electronics by looking for hot components, damaged components, or stay wires causing shorts.

Microcontroller:

a. Ensure the electronics are deenergized.
b. Attach the JTAG connector to either the PCB (P2) or the JTAG bulkhead (clearly labeled).
c. Attach to the JTAG connector a JTAG programmer of your choice.
d. Energize electronics. Ensure power LEDs turn on as described in 1.g (i-iii). If not, there is likely a short. Do not continue testing procedures.
e. Attempt to program the microcontroller using Code Composer Studio or an environment of your choice. You may use any program for this test that does not command the motors (a while loop that does nothing is suggested, but something that toggles D4-D6 may also be interesting).
f. If programming succeeds, the microcontroller is functioning. If programming fails, the microcontroller is likely faulty. **A faulty microcontroller likely requires the placement of a new device.**

UART Communications:

a. Attach a USB cable to the USB bulkhead on the enclosure.
b. Using the attached JTAG device from step two, write to the microcontroller a UART test program. This program should echo characters from the terminal.
c. Using PuTTY or another serial terminal of one's choice, test the echo program
d. If this test fails, the UART communications have failed. Either:
    i. The UART on the microcontroller is faulty
    ii. The onboard UART-to-USB chip is faulty
    iii. The drop-in device-to-UART dongle is faulty (e.g. Bluetooth to UART)
    iv. The connections between the device and the PCB is faulty.
e. To debug the above
    i. First test continuity of all wires tied to the UART line.
    ii. Then, test the USB cable(s) functionality.
    iii. If using external UART-to-device tools, test their functionality and ensure the following resistors were removed from the PCB: R7, R9, R10, R11
    iv. If using the onboard UART-to-USB device, try using an external UART-to-USB device (e.g. SparkFun Dev-09873). You may use P1 for this test. Ensure resistors R7, R9, R10, and R11 are removed from the PCB for this test.
    v. If all of the aforementioned appear to be functional, assume the microcontroller is faulty. **A faulty microcontroller likely requires the placement of a new device.**

Encoders:

a. Ensure the electronics are deenergized.
b. Ensure encoders are properly installed on motor drive shafts. Follow the Renishaw/RLS guidelines set forth in their datasheet to ensure the redhead and magnetic ring are properly aligned.
c. Connect the encoder to the electronics via the properly labeled bulkhead on the electronics housing for either motor 1 or motor 2.
d. Energize electronics. Ensure power LEDs turn on as described in 1.g (i-iii). If not, there is likely a short. Do not continue testing procedures.
e. Ensure the microcontroller has been loaded with the primarily packaged software or software that tests encoder functionality.
f. Check the encoders' status LEDs. The LEDs should be solid green shortly after turning on the electronics. If not:
    i. RED/ORANGE: misalignment of encoders. See mechanical debugging guidelines
    ii. GREEN BLINKING: no alignment issues, no clock signal from microcontroller. This is a software issue. Try flashing the microcontroller with the packaged code to test.
g. After verifying encoder LED status, use the software interface (see software guidelines) to ensure proper functionality. Suggested testing:
    i. ¼ turn – do the encoder values increase by 90 degrees?
    ii. ½ turn – do the encoder values increase by 180 degrees?
    iii. Full turn of encoder – do the encoder values increase by 360 degrees
    iv. Failure of any of the above indicates an error with either the software or the encoder. If an encoder fails, contact Renishaw to purchase a replacement read head or repair the device if its warranty remains active.
h. If the encoders do not function, **do not proceed to test the motors.**

Motors and Halls:

a. Ensure the electronics are deenergized.
b. Connect motors and halls to the electronics via the properly labeled motor and halls bulkheads.
c. Connect encoders to electronics enclosure if removed from step 4.
d. Energize electronics. Ensure power LEDs turn on as described in 1.g (i-iii). If not, there is likely a short. Do not continue testing procedures.
e. Monitor electronics and motor temperature (via a temperature probe) to ensure no electronics appear to increase in temperature.
f. Ensure all hardware is properly clamped to the workbench.
g. Using the provided software, command each motor, one at a time, to move in both the positive and negative directions using PWM commands as described in Table 6.
    i. During both the first and second tests, press the emergency stop button located on the side of the electronics housing. Ensure the

motor stops spinning in both cases. **If the E-Stop does not stop the motors, do not proceed, a critical failure has occurred and the system is not safe for use.**

ii. After a pressing the E-Stop, release it. The electronics motors should move again. If they do not, reset the system via the reset button also located on the electronics enclosure. If the reset button does not work, power cycle the system. If the motors still do not spin**, a critical failure has occurred and the system is not safe for use.**

iii. If the procedures pass with success, continue the testing described in Table 6.

Table 1: Motor Testing Sequence

M1 Command	M2 Command	M1 Behavior	M2 Behavior
10	0	Spins slowly CW	No motion
0	10	No motion	Spins slowly CW
-10	0	Spins slowly CCW	No motion
0	-10	No motion	Spins slowly CCW
10	10	Spins slowly CW	Spins slowly CW
-10	10	Spins Slowly CCW	Spins slowly CW
50	0	Spins FAST CW	No motion
0	50	No motion	Spins FAST CW
50	50	Spins FAST CW	Spins FAST CW
-50	50	Spins FAST CCW	Spins FAST CW

h. If all tests behave as described, the system is behaving as designed and is ready for classroom use. If not, a motor controller or motor may be damaged. **Do not continue to commission the device if this scenario occurs. Contact support staff.**

Electrical

To improve the R2R learning robot's electronics, the following next steps are suggested for implementation. It must be noted that this is not an exhaustive list.

- The two motor controllers may be placed closer together to shrink the size of the control electronics. This will lower manufacturing costs.
- Placing components on both the top and bottom layers of the PCB to further shrink the electronics. This is likely a cost-neutral revision.
- The voltage input range may be shrunk from a range of 22V-56VDC to a range of 22 - 36VDC. This will allow for the following improvements:
  - The relaxation of the voltage rating requirements for the motor controller's bulk capacitors; this allows for physically smaller and cheaper capacitors to be user.
  - The use of lower input voltage DC-to-DC regulators; this allows for lower cost and physically smaller 3.3V and 5V DC-to-DC regulators. Further, this minimizes the regulator's support circuitry requirements and will further shrink the 3.3V and 5V regulator's footprints.
  - The use of more accessible and lower cost power electronics on the input voltage protection lines.
- The removal of testing components to lower cost and bring the PCB closer to a full production device. This also includes "tenting" all exposed vias to protect the board from environmental shorting.
- Implementation of the force sensor and IMU, first via existing electronics, and then via novel designs to implement more advanced sensing hardware.

Electrical System Incidents

Following PCB fabrication, an unfortunate number of electrical design issues arose. All are documented here with causes and fixes, both implemented and proposed. All are documented in the order of appearance. Detailed solutions to all issues are provided in electrical next steps, electrical changes (from First Board to Second), evolution of electronic design sections. All reference designators mentioned refer to the designators in the final version of the schematics.

Incident: System does not energize
Issue: V_{zeener} on input power protection diode (D9) too low; short from input power to ground created.
Solution: Remove diode, replace with diode with higher V_{zeener} rating. Replace part number in design files.

Incident: 3.3V, 5V rails did not supply power
Issue: D12, D15 facing wrong direction creating a short from 3.3V and 5V to ground
Solution: Remove D12 and D15 and flip component on PCB. Rotate component in design files.

Incident: Failed JTAG communication/programming
Issue: (1) Core voltage of microcontroller (pin 115 on U2D) shorted to ground; (2) mirrored crystal oscillator PCB footprint
Solution: (1) Cut trace between pins 114 and 115, short pin 115 to pin 87 as described in microcontroller data sheet. Correct design files with new traces in layout. (2) Remove crystal oscillator and use internal oscillator for prototype, use proper footprint in design files.

Incident: 3.3V bus fire, irreparably damaging entire PCB
Issue: Metal shavings and loose wires visibly present on workbench, created short on 3.3V regulator output
Solution: Prepare new prototype PCB, clean work bench, implement new PCB handling procedures.

Incident: Electrostatic discharge event, irreparably damaging microcontroller
Issue: Improper grounding of engineer, lack of ESD protection on PCB
Solution: implementation of ESD protection for engineers at workbench, addition of fast-acting TVS diodes on all voltage buses (in design files) to short all voltage spike above ~10% V_{bus} to ground

Incident: Twice noticed, visible and audible arc flashes on motor power bus on PCB
Issue: Excess energy storage in motor windings (acting as a large inductor) during improper commutation creating a capacitive environment; build-up of charge between high current sourcing traces supplying pins 1 and 2 of header P16 (motor supply), leading to short on lines on PCB as the result of exposed vias (non-tented) and close via placement; arcing possible as the result of >~ 10 mils spacing between high energy vias.
Solution: At manufacturing time, request all vias to be tented. After manufacturing and PCB testing, apply a high-temperature conformal coating to all PCB components.