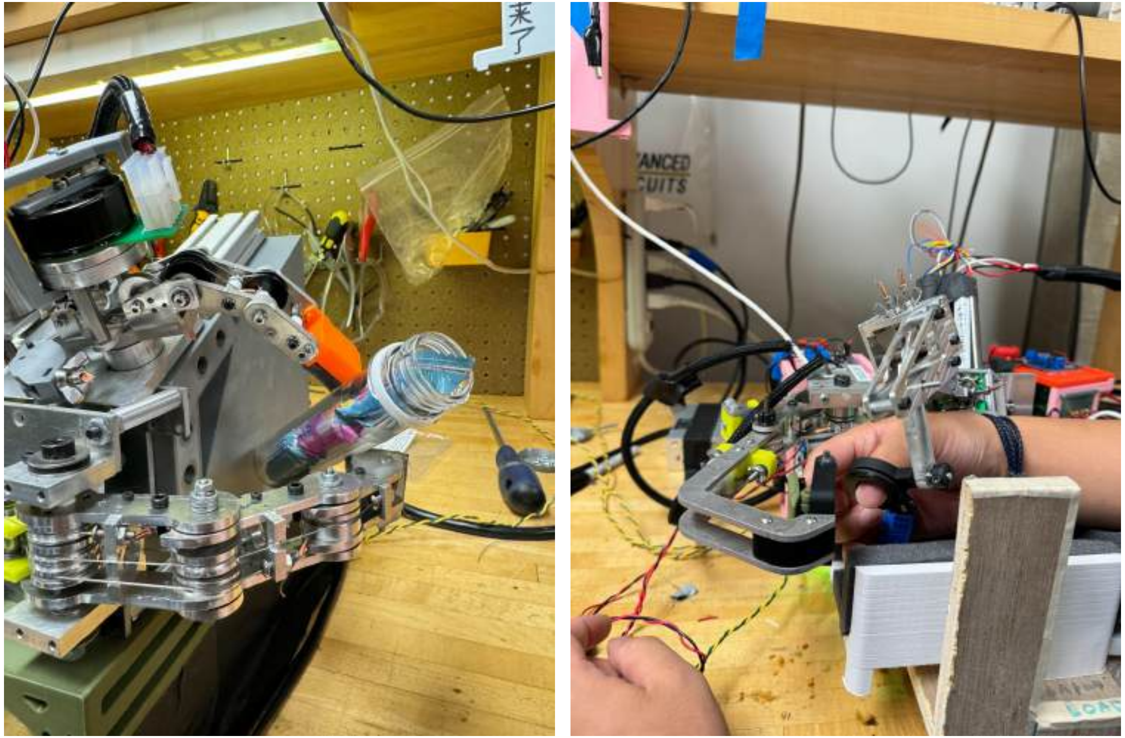
RDS Final Presentation

Spring 2024



Background

- Objectives
    - Teleoperation in nuclear “hotbox” environment
    - Dextrous manipulation
        - Laboratory tasks
            - Pinch, twist wing nut, hold flasks
- Requirements
    - High stiffness and force transparency
        - No “nerf world”
    - Low reflected inertia → easily backdrivable
        - Keep transmission ratios low
    - Large workspace
        - Match human fingers and thumbs

Sneak Peek

Specs

Bilateral Control	Max stiffness	400N/m on finger 3Nm/rad on thumb waggle, 1N/m/rad on thumb curl
	Update rate	1000Hz
	Latency	~1ms
Haptic Finger	Range of motion	Straight finger to full curl
	Max Force	~4 - 12 N at end
Robot Finger	Range of motion	Straight finger to full curl of PIP joint
	Max Force	~5 - 15 N at end
Robot Thumb	Range of motion	Straight thumb to full curl, side-to-side “waggle” motion
	Torque	~ 1.0 Nm
Haptic Thumb	Range of motion	Straight thumb to full curl, 70° side-to-side “waggle” motion
	Torque	~0.8 Nm

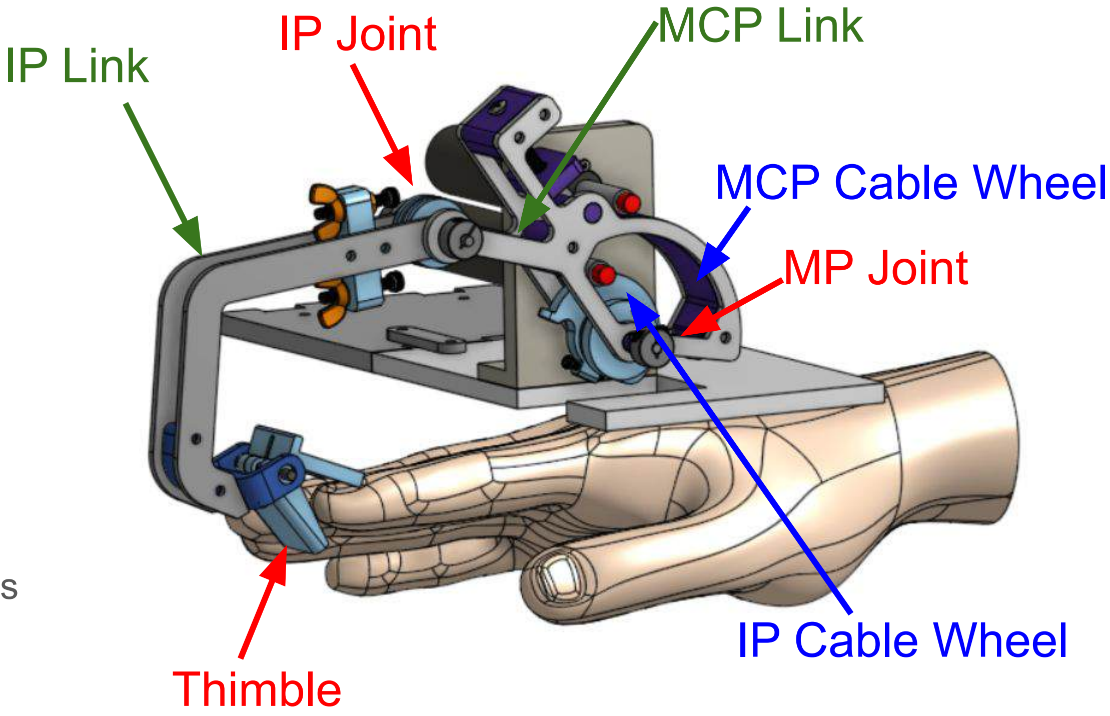
Agenda

1. Mechanical design
2. Power
3. Electronics
4. Startup
5. Control
6. Safety

Mechanical Design

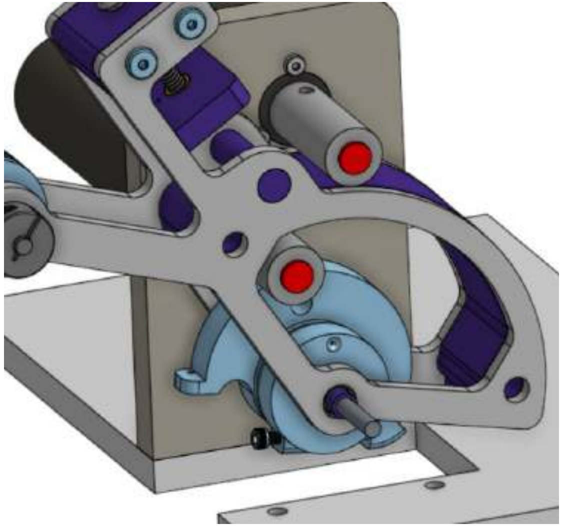
Haptic Finger

- 2 actuated DOF + 1 passive DOF
- Cable drive transmission
  - 6.2:1 MP Joint
  - 3.6:1 IP Joint
  - Cables terminated at tension screws
    - Vented screws + wing nuts
    - Stainless steel cable
- Maxon ECX Torque 22XL motors
  - High torque, low rotor inertia
  - Magnetic motor encoders

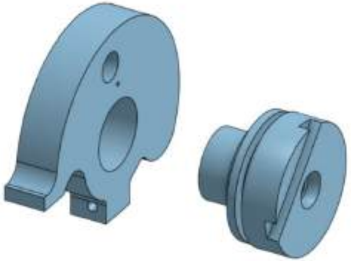


Cable Wheels

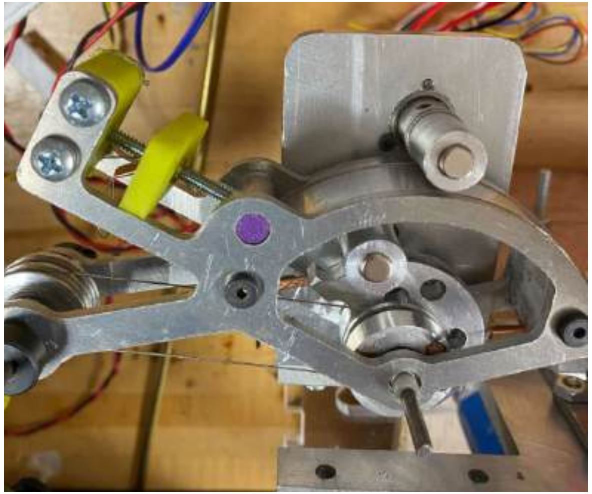
- Nested cable wheels independently rotate on fixed shaft
    - Reduces space requirements
    - Only one motor and encoder mount needed
    - Keeps all forces (mostly) in same plane
    - More difficult assembly
    - Imposes joint limits



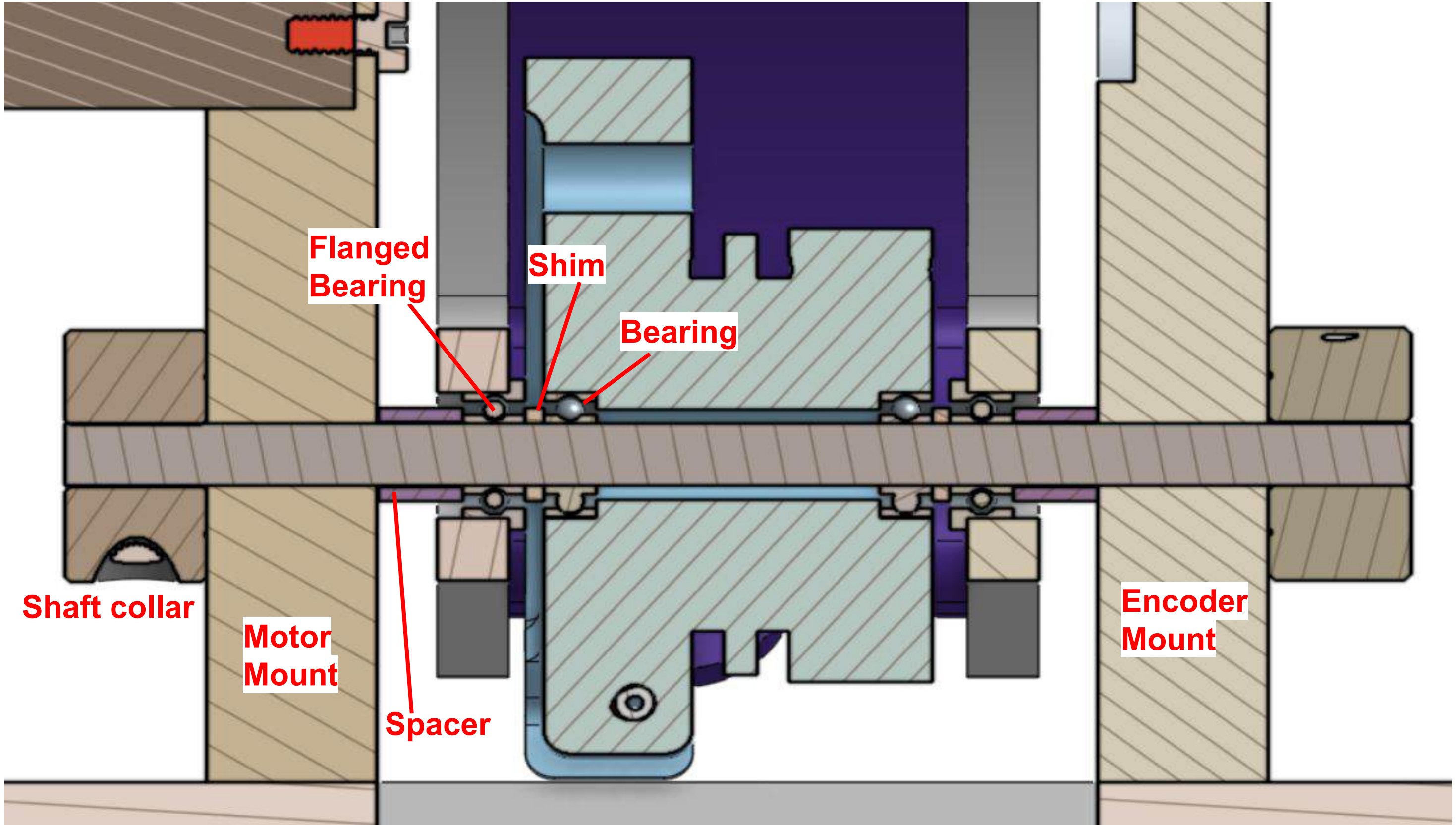
IP Wheel



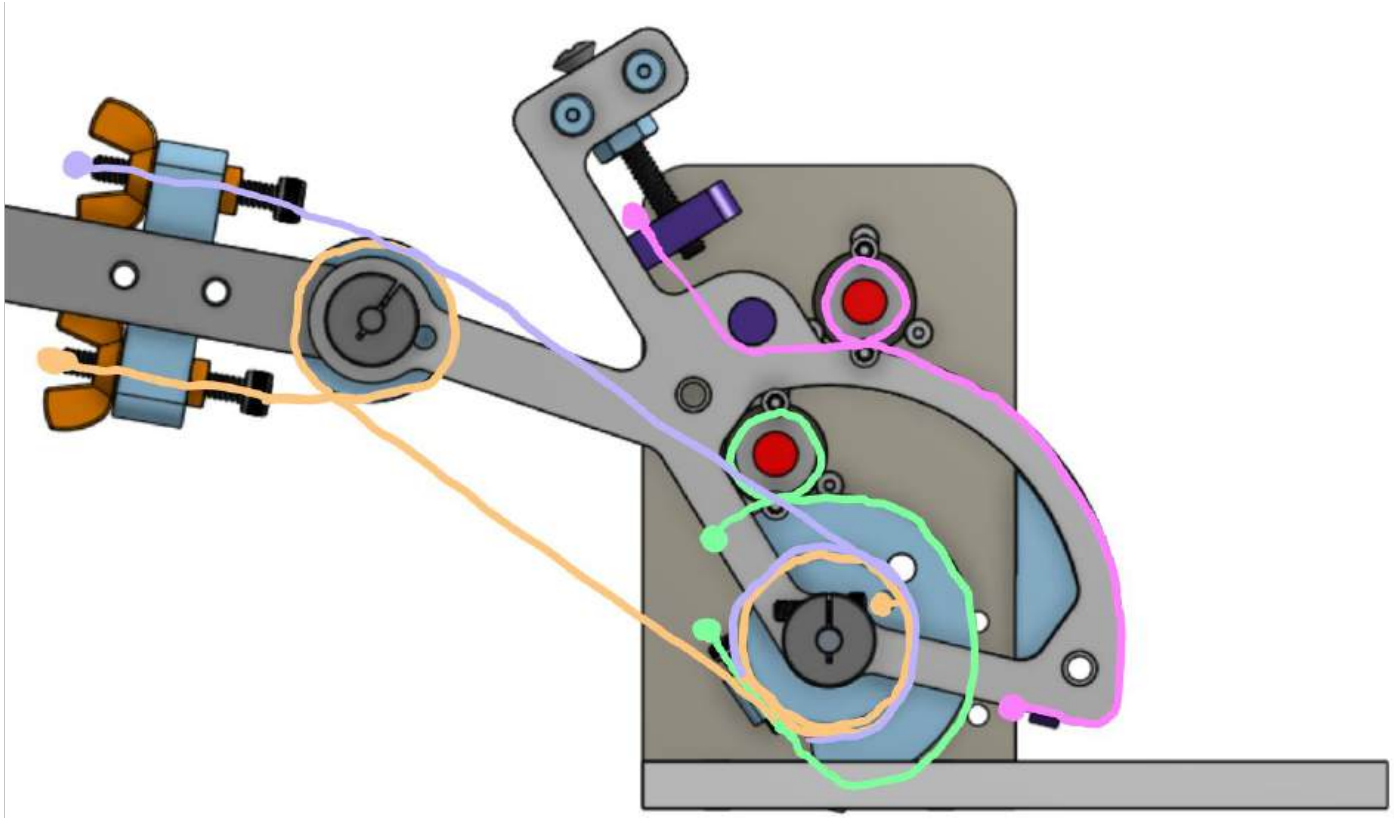
MP Wheel



Shaft Cross Section



Cable Routing



Haptic Finger - Key Lessons

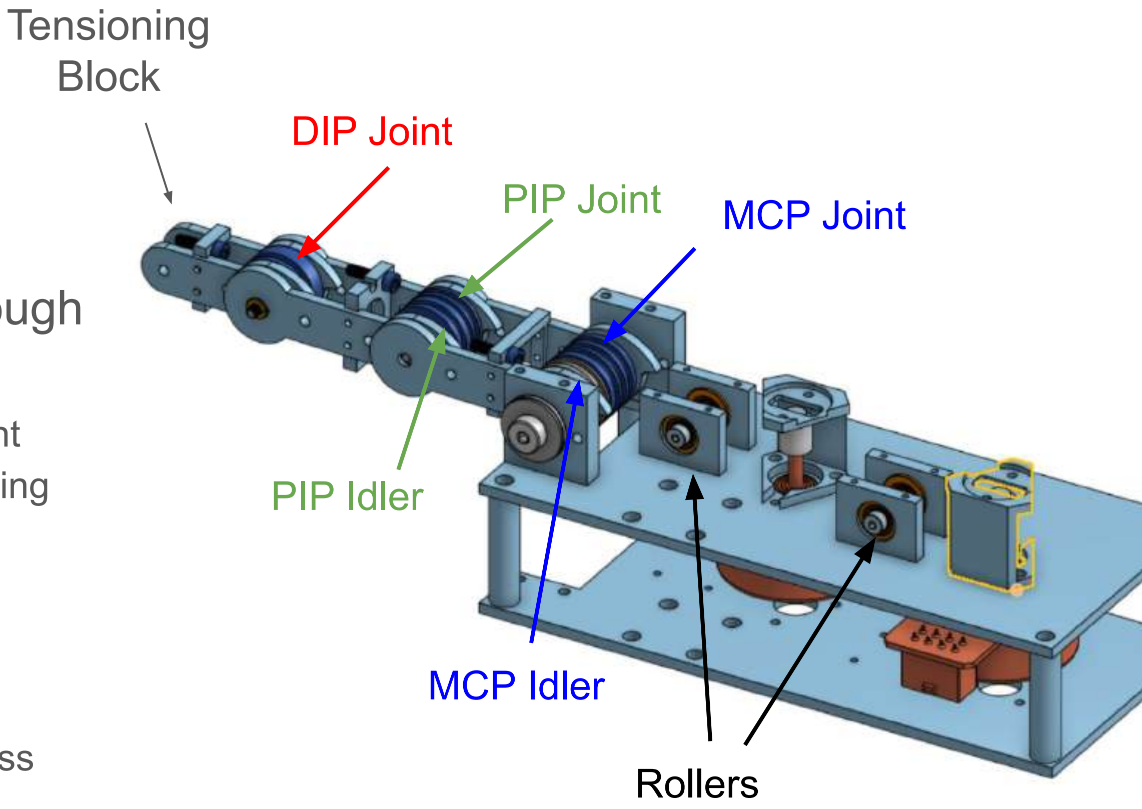
Strengths:

- Simple assembly and repair (30 minute total assembly, 10 minute cable repair)
- Intuitive wingnut tensioning with vented screws
- Achieves full finger range of motion (in plane)

Weaknesses:

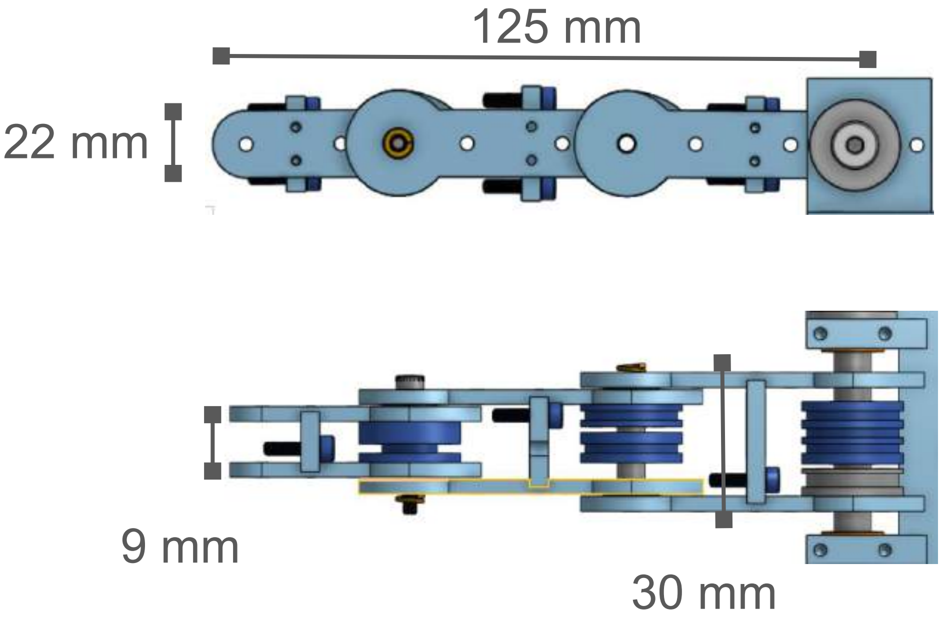
- Small bearings and shafts
  - Require higher tolerances
- IP wheel cable is most frustrating to repair due to lack of wingnut
- Floating cable terminations

- 2 Actuated DOF
- Transmission achieved through pulleys
  - 4:1 transmission for every joint
  - Cables terminated on tensioning screws
    - Vented Screws + Nuts
    - Coated Steel Cable
- EC 45 Flat motors
  - Cheap, High Torque, Low Mass
  - Higher Rotor Inertia



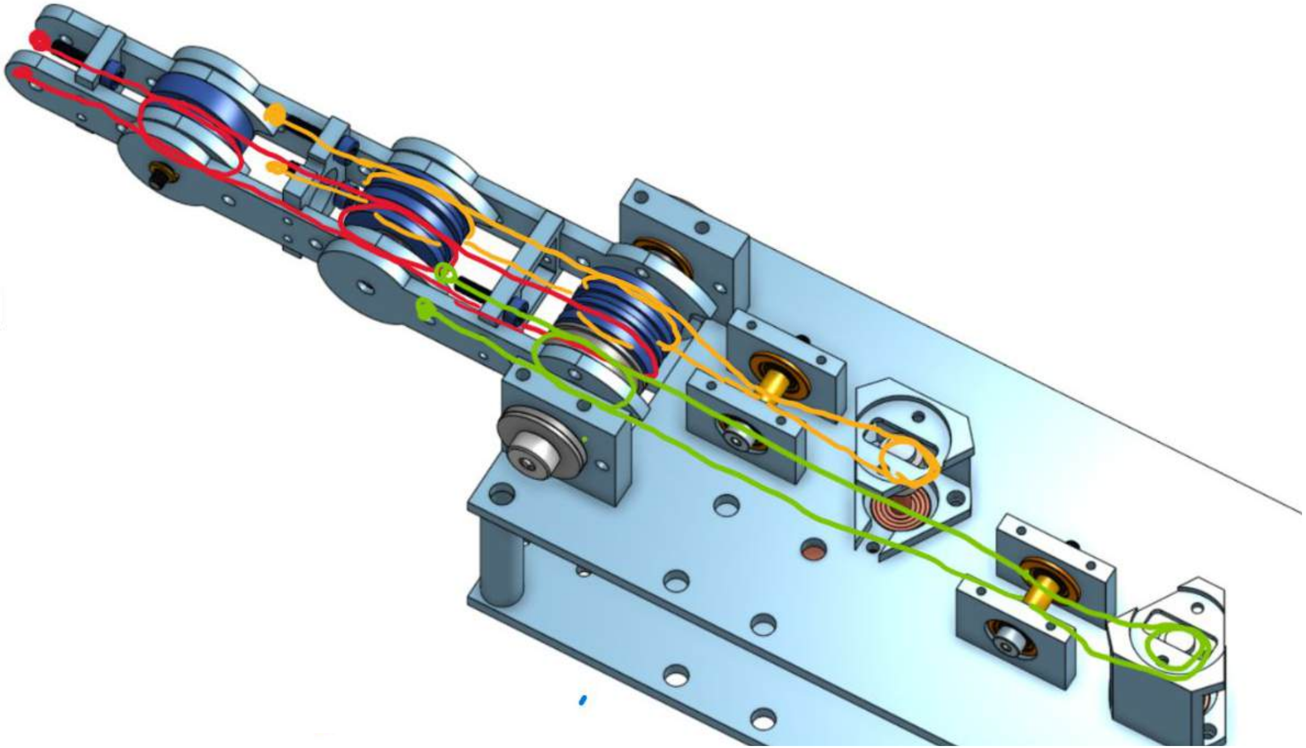
Robot Finger

- Form Factor:
    - Robot Finger Dim
    - Human Finger Dim
- Design Forces and Torques:
    - 1 Nm
    - 20 N output at the FingerTip
- Manufacture:
    - Water Jet Mounting Plates
    - CNC Milled Links
    - Turned Pulleys

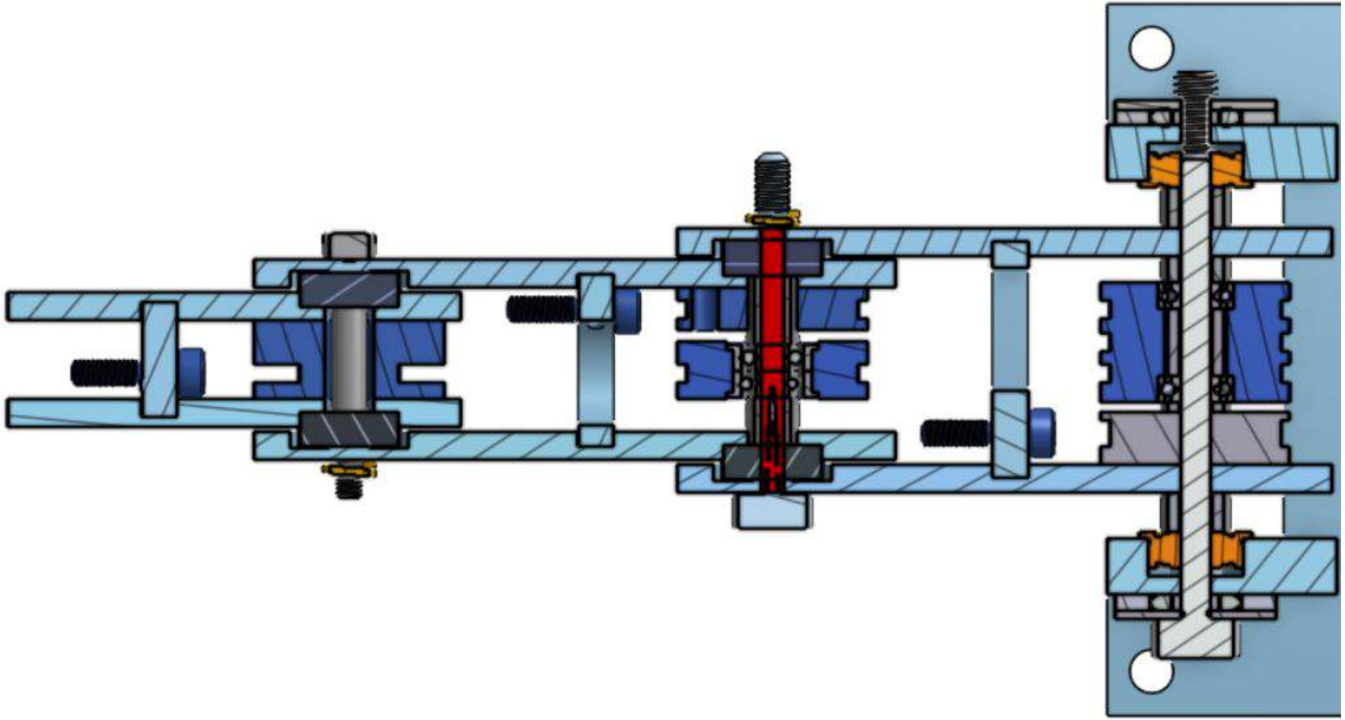


Human Dimensions	
Finger Width [1]	20.3 ± 2.4 mm
Finger Length* [2]	77.74 ± 6.37 mm

Robot Finger – Cable Routing



Robot Finger - Link Section View



Robot Finger – Key lessons

Strengths:

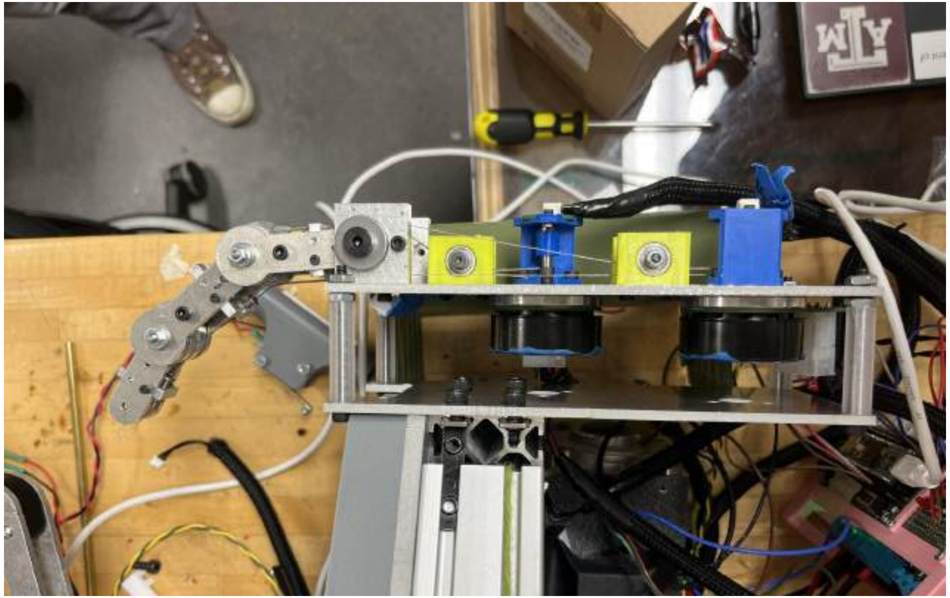
- Relatively Compact System
- Tensioning System Rarely Slips
- Capable of outputting large torques.

Weaknesses:

- Coupling requires loose tensioning
- Assembly is time consuming
- Variable Width of Finger

Future Work:

- Make system even more compact



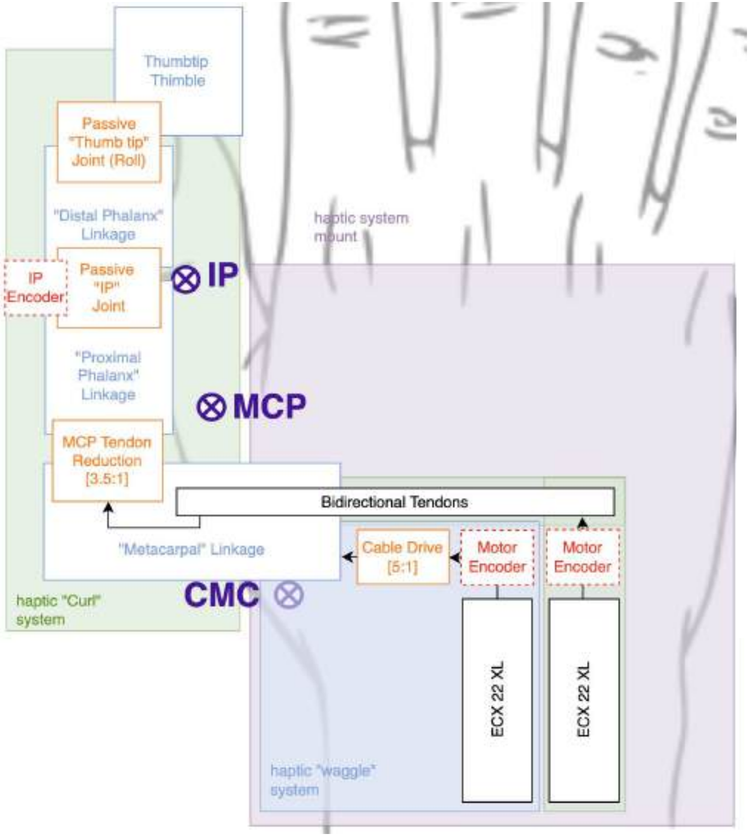
Haptic Thumb - System Overview

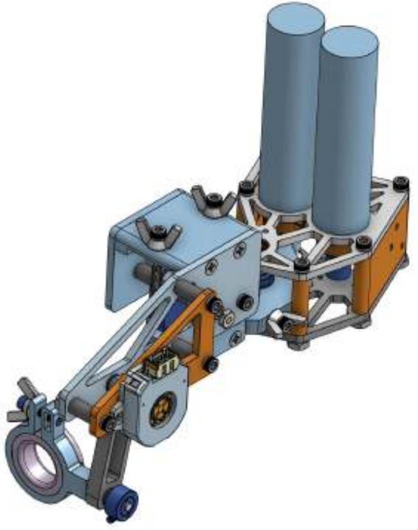
- **“Waggle”** (1 active)
  - “CMC”: Active

[60° wrt palm plane]

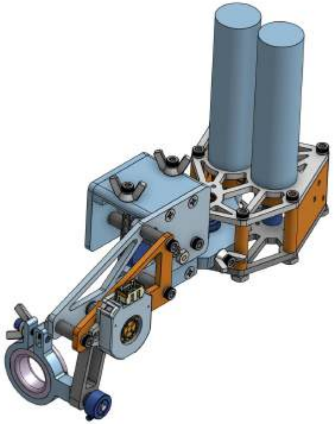
- **“Curl”** (1 active, 2 passive)
  - “MCP”: Active
  - “IP”: Passive
  - “Thumb tip”: Passive

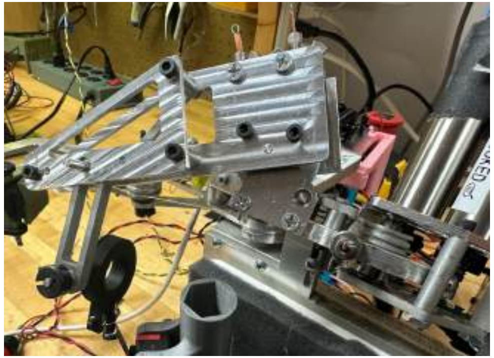
[90° wrt waggle plane]





Haptic Thumb - System Overview



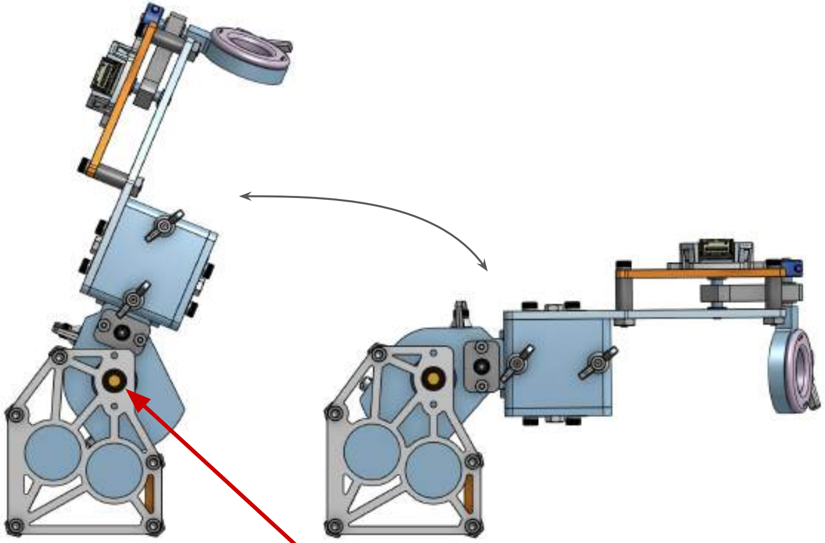


“Curl motion”

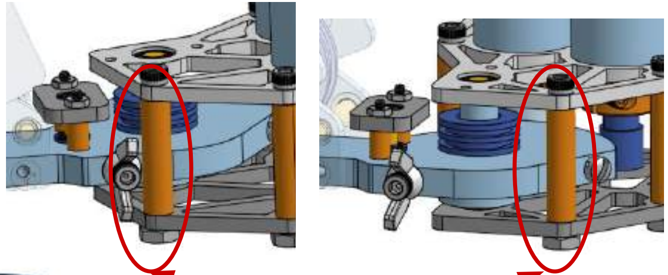
“Waggle motion”

CMC: Active Thumb Waggle

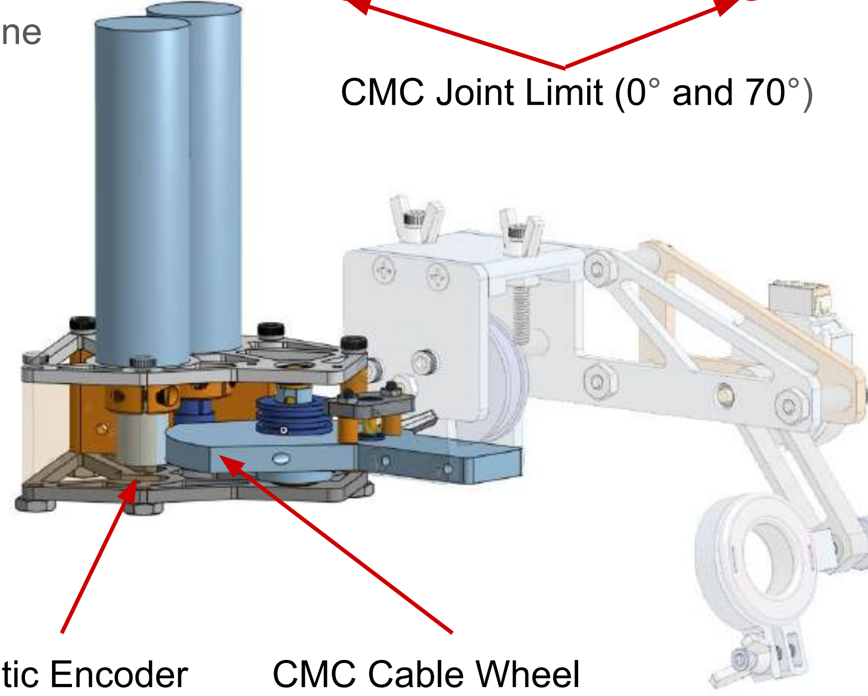
- 70° ROM, ~5:1 Cable Drive Transmission
- Thumb plane oriented 60° from palm plane



CMC Joint



CMC Joint Limit (0° and 70°)

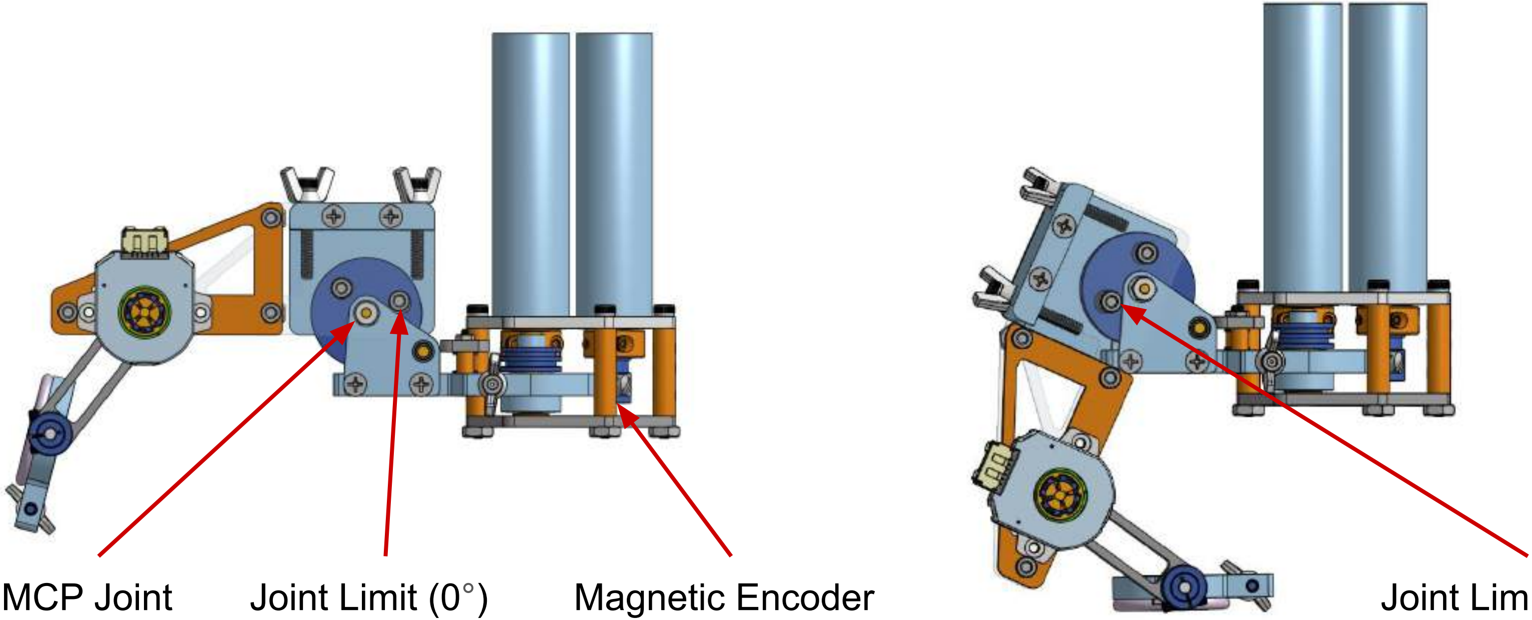


Magnetic Encoder

CMC Cable Wheel

MCP: Active Thumb Curl

77° ROM, ~3.5:1 Cable Drive Transmission



MCP Joint

Joint Limit (0°)

Magnetic Encoder

Joint Limit (77°)

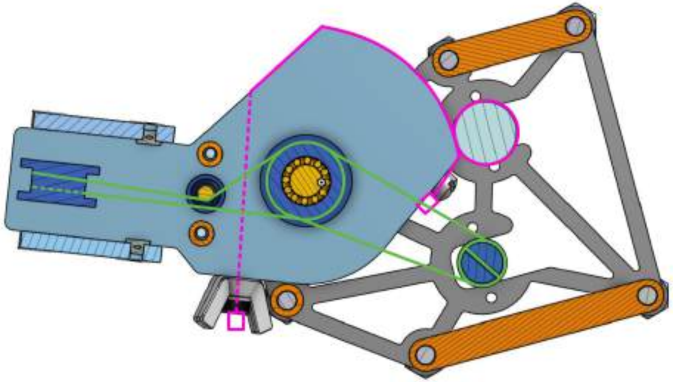
Haptic Thumb - Cable Routing/Tensioning

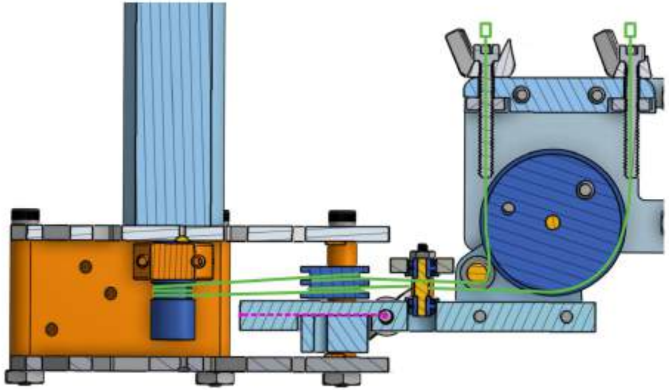
CMC Cable Drive:

- **Vented screw tensioning** on one end (Terminated at wire-lockable screw)
- Three full wraps around motor pulley

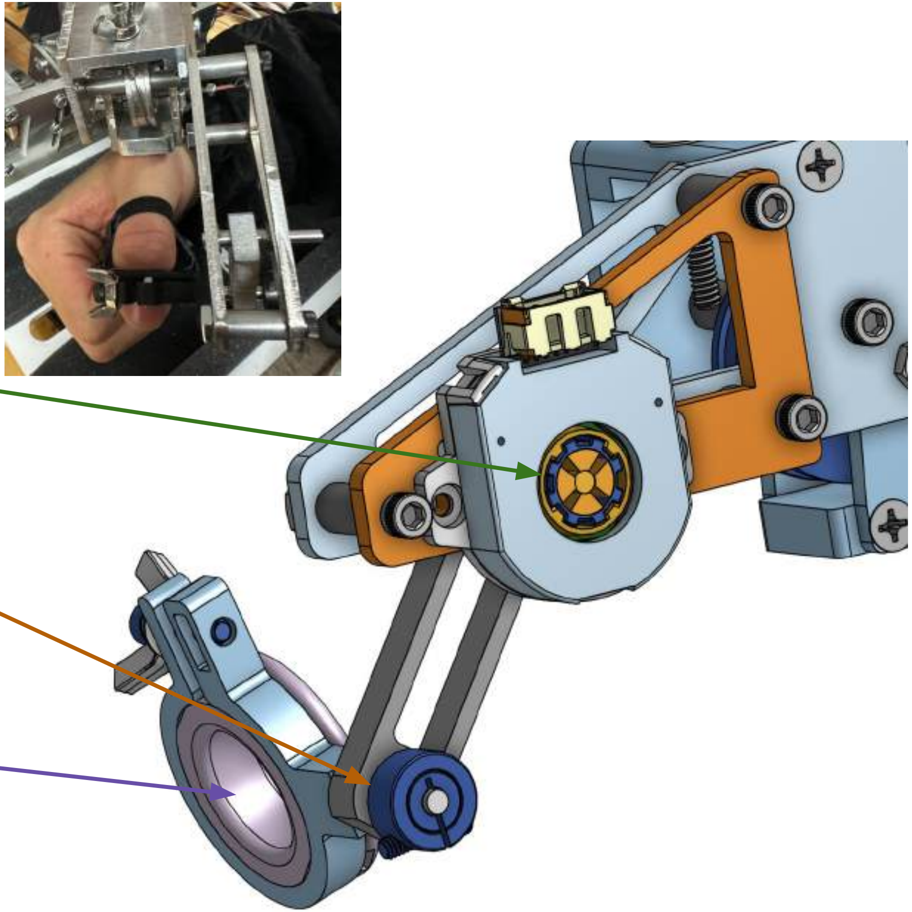
MCP Bidirectional tendon:

- **Vented screw tensioning** on both ends
- Three full wraps around motor pulley (Slot in middle to reduce slippage)
- Routing achieved by **three idlers**: CMC shaft, horizontal positioning, vertical positioning)





Haptic Thumb - Comfort



- Cantilevered system
- Passive IP joint:
  - Monitored by absolute capacitive encoder (AMT22)
- Passive Thumb tip joint
  - Thumb tip pitch at center
- Removable thimble
  - Multiple diameters for proper fit

Haptic Thumb - Lessons Learned

Strengths:

- Tensioning produces **little to no cable slippage**
- Robust **mounting** and **mechanical limits**
- Passive degrees of freedom provide **user comfort** during curl

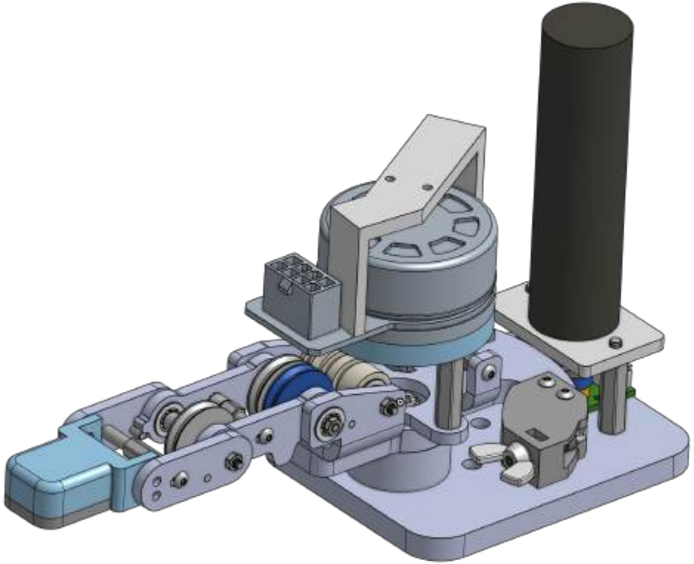
Weaknesses:

- **Friction** in actuated MCP joint
- Cable routing **couples MCP and CMC joints**
- **Complex** cable routing/system assembly

Future Directions:

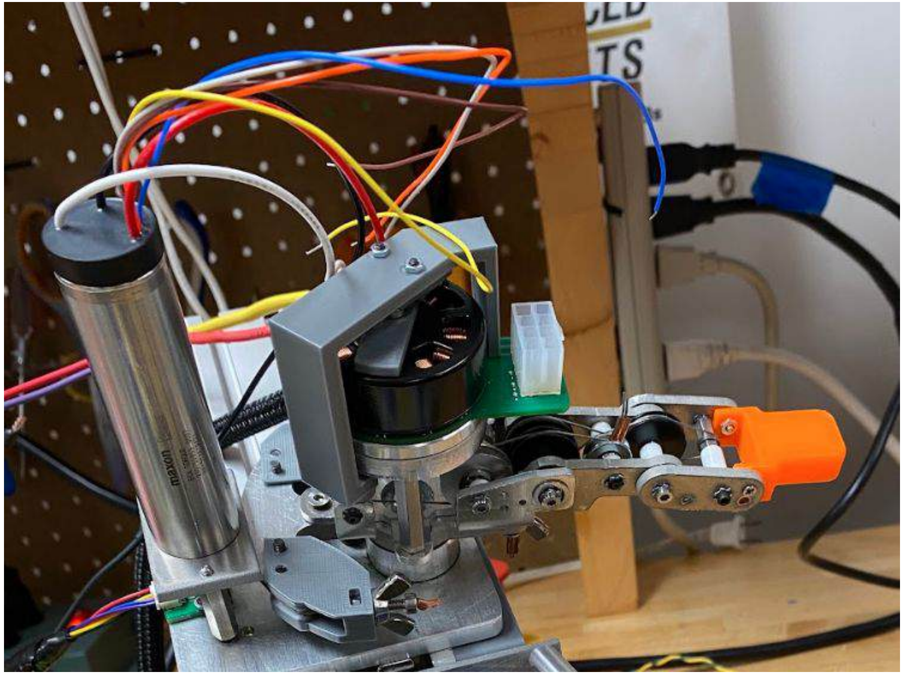
- **Higher fidelity thumb tip**-thimble interface (Possible roll implementation)
- Improve machining tolerances and **increase design tolerances** along the cable routing path
- **Mitigate friction** at the MCP joint

Robot Thumb



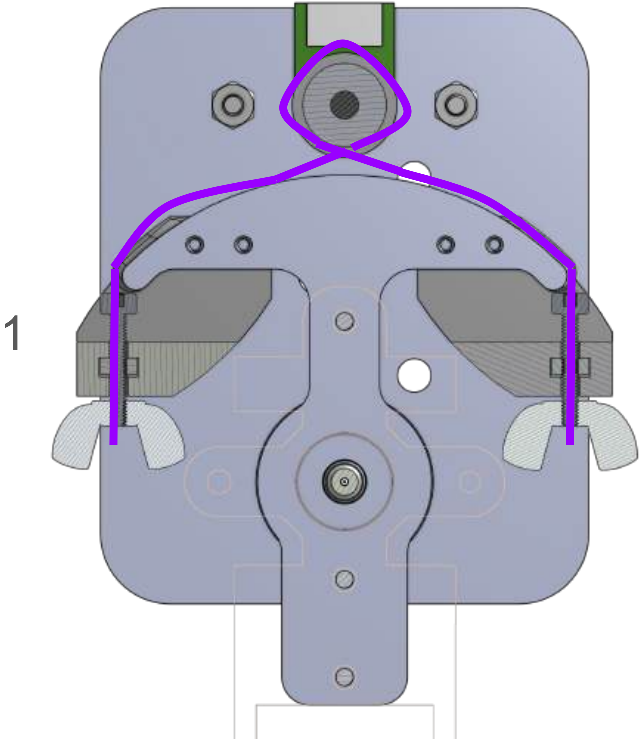
Overview

- 2 Actuated DOF
- Mimicking Human Thumb Kinematics
  - Waggle Joint
  - Coupled Curl Joints
- Tendon system
  - 4 routes overall
  - Nylon coated steel braided cable
- Cable Drive - “Waggle”
  - Maxon EXC Torque 22XL
  - Transmission Ratio 7.3:1
- Curl
  - Maxon EC 45 FLAT
  - Transmission Ratio 7.94:1
  - Around 1.6Nm of Torque

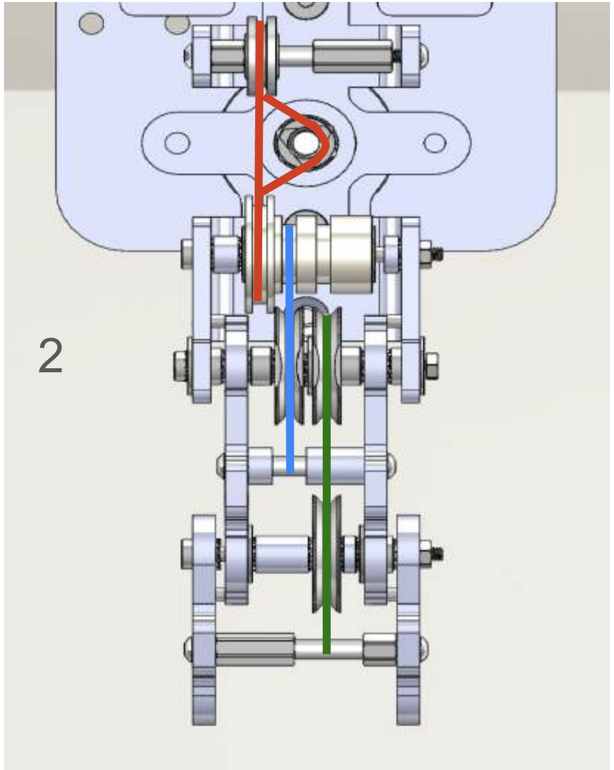


Cable Routing and Tensioning

Waggle



Curl



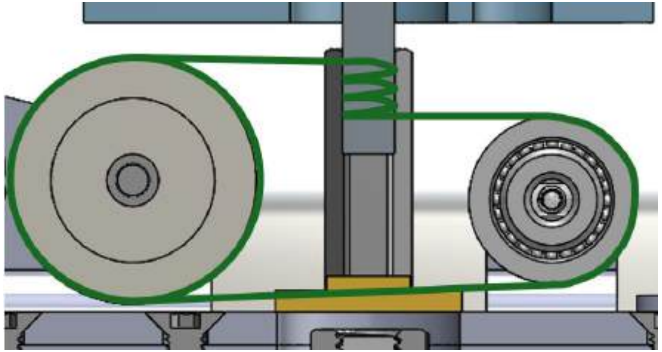
Cables:

- 4 tendon routes
- Steel braided cable
- Red, blue, green – all coupled to achieve curl
- Multiple wraps to prevent slippage

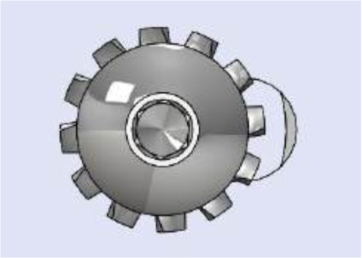
Tensioning is achieved through:

1. Wing nut and screw combinations
2. Sliding tendon tie-off points

Pulley Design and Tensioning Continued

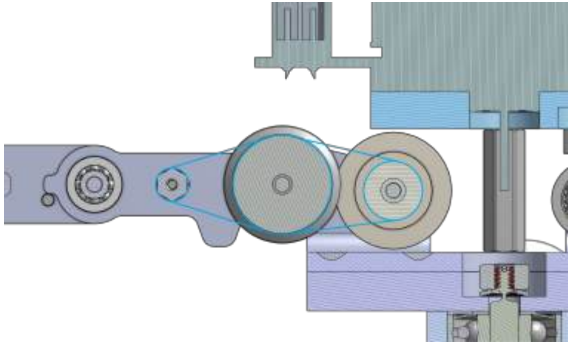


3 wraps - 7 wraps - 0 wraps

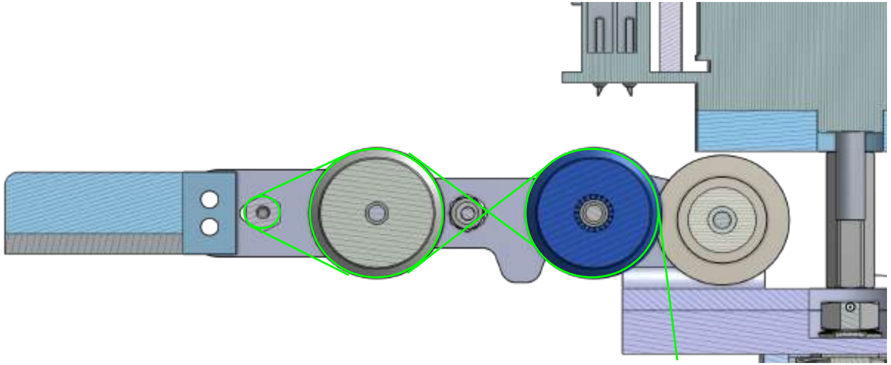


- External Tooth Lock Washers secure links and tensioning joints

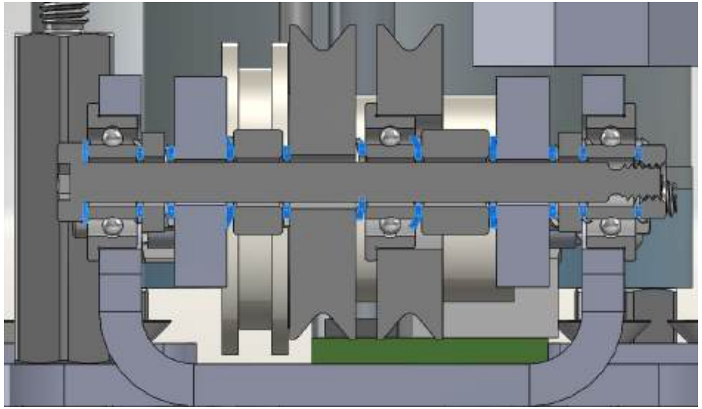
- Constructed of 18-8 stainless steel and in compliance with ASME B18.21.1



1 wrap - 2 wraps - 4 wraps

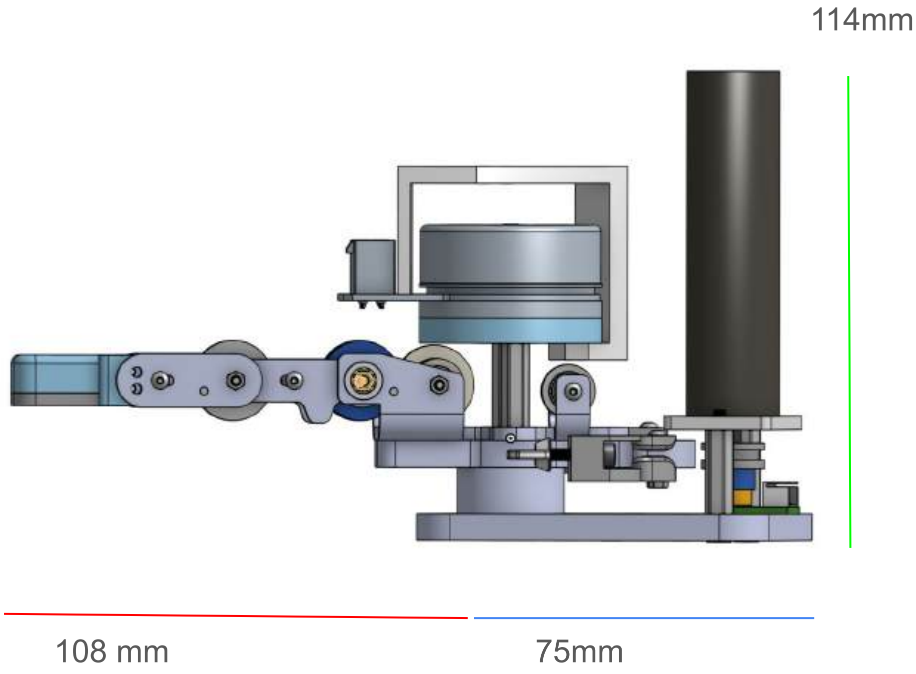


1 wrap - 2 wraps - 2 wraps - Fixed



Manufacturing

Form factor:



Manufacturing methods and materials:

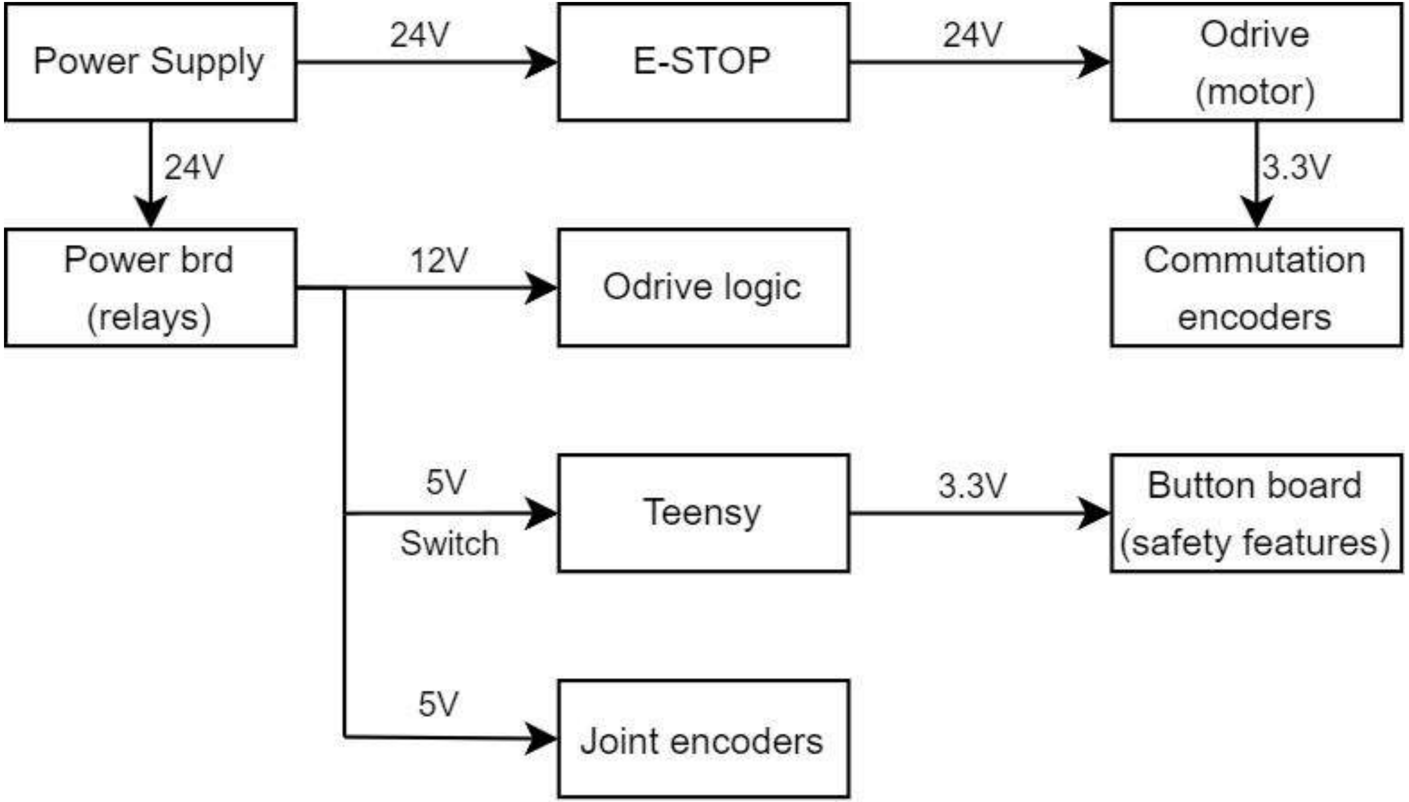
- Aluminum plates, 3D printed PLA parts (spacers, tensioning, end effector), McMaster components (ie bearings, nuts, etc.)
- Milling / lathe machines
- Water Jetting
- Send-cut-send laser cutting
- Held together by bolts, press fits, “push fits,” and locktight
- Designed for disassembly

Lessons Learned

- Strengths
  - Curl link coupling
  - Motion capabilities given 2 actuators
  - Manufacturability (assembly and disassembly)
- Weaknesses
  - Tendons difficult to tension
  - Some regions where the tendons rub against each other or another part
  - Form factor / mounting in relation to robot finger
- Future changes
  - Update tensioning method
  - Adjustments to cable routing design
  - Adjustments to form factor / mounting for better synergy with robot finger

Electronics

Overall Power Architecture



Power Supply

24V

E-STOP

24V

Odrive (motor)

24V

3.3V

Power brd (relays)

12V

Odrive logic

Commutation encoders

5V

Switch

Teensy

3.3V

Button board (safety features)

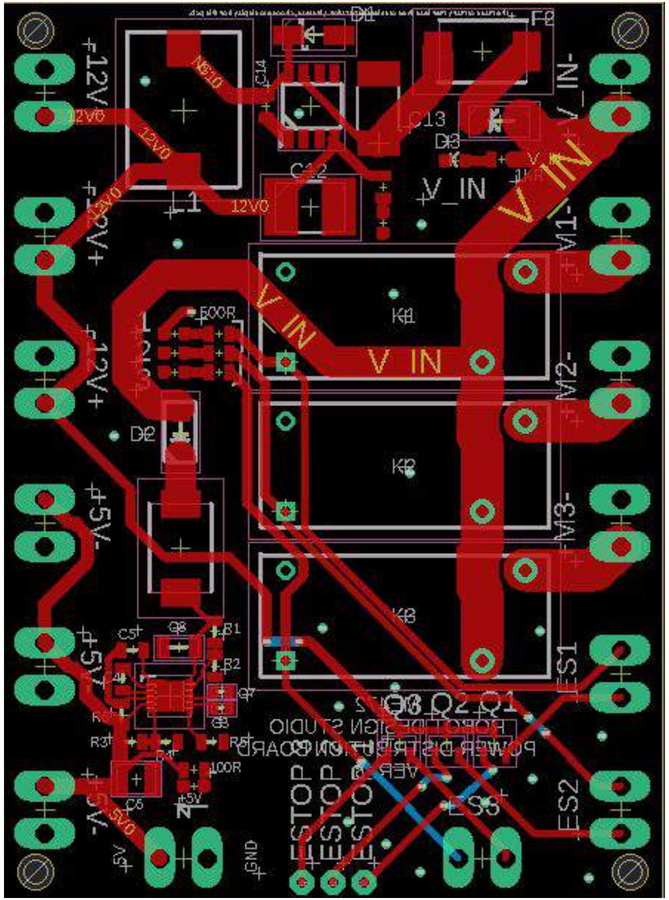
5V

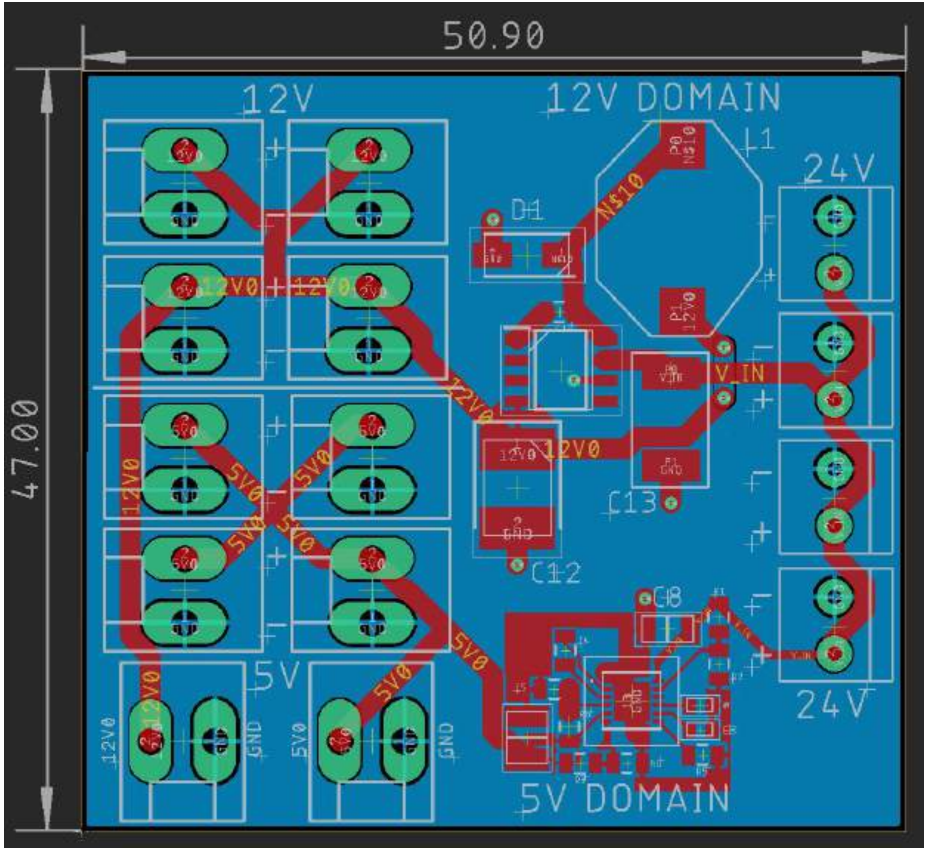
Joint encoders

Data and Power Boards

Buckle up, buttercup

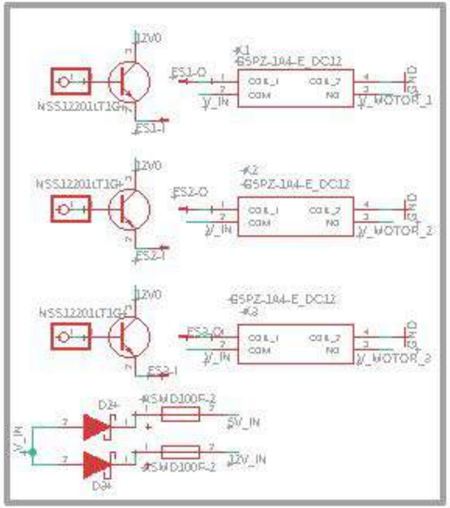
New v.s. Old Power Board





Overall Power Board Schematic

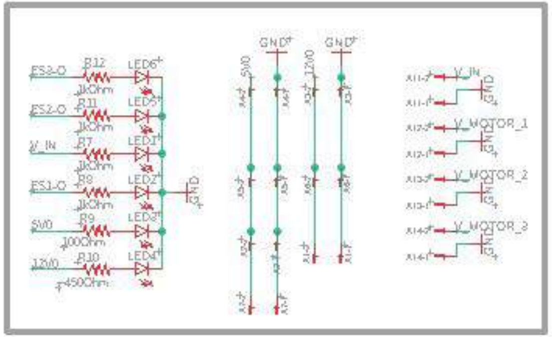
Relays, Polyfuse, Diodes



TRANSIENT SUPRESSION, DIGITAL E-STOP, PHYSICAL E-STOP

NOTES:
-RELAY CONTROLLED BY GPIO FROM DATA BOARD
-PTC THERMISTORS LIMIT 2.2 AMP SURGE

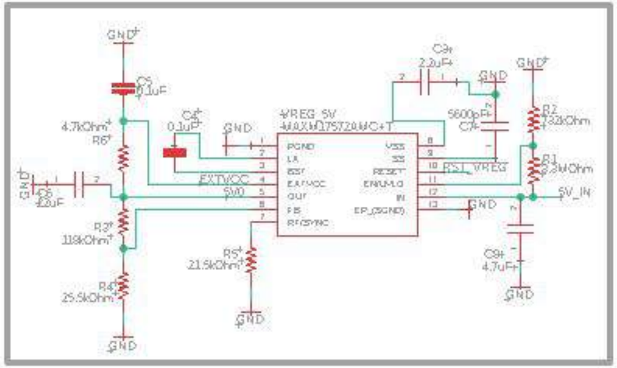
I/O and Indicators



POWER I/O & INDICATORS

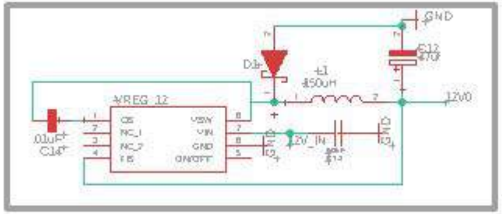
NOTES:
3.5MM TERMINAL
2.54MM CONNECTORS

5V Regulation



5V SWITCHING BUCK REGULATOR CIRCUIT
IN: 24VDC
OUT: 5VDC 1A

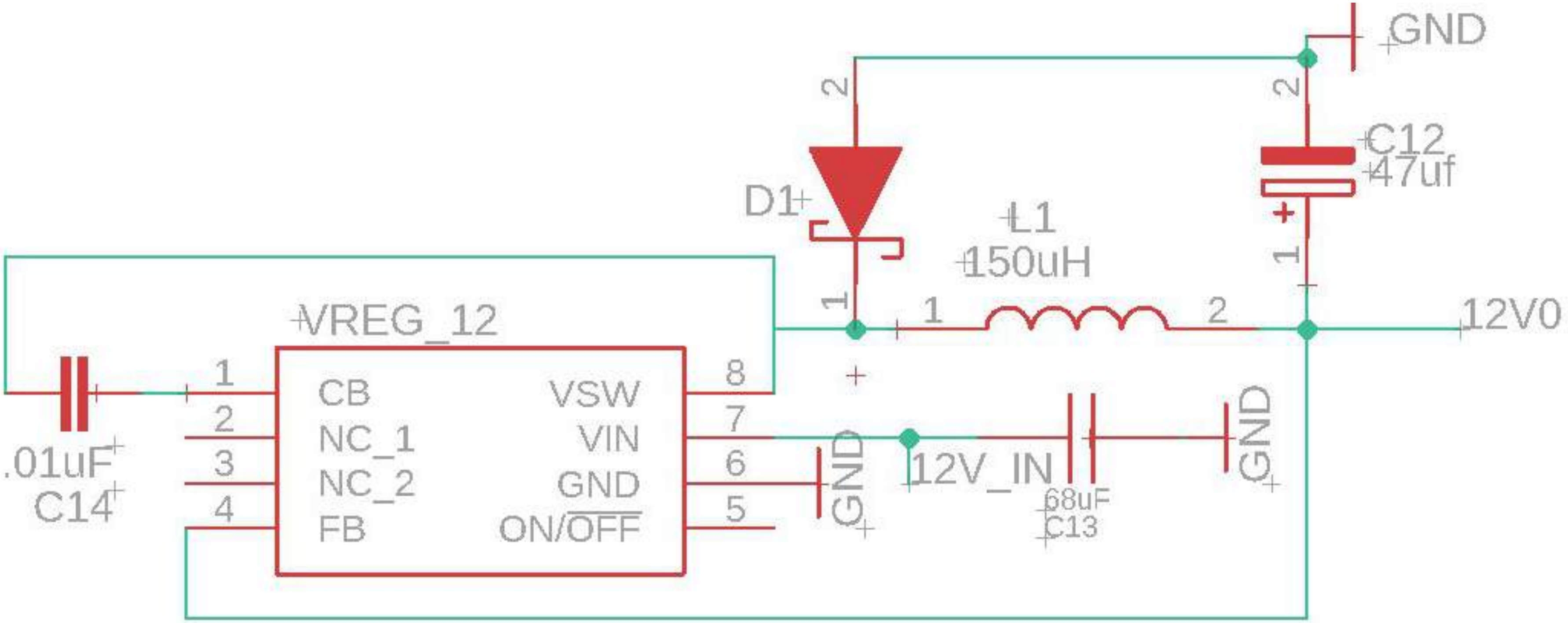
12V Regulation



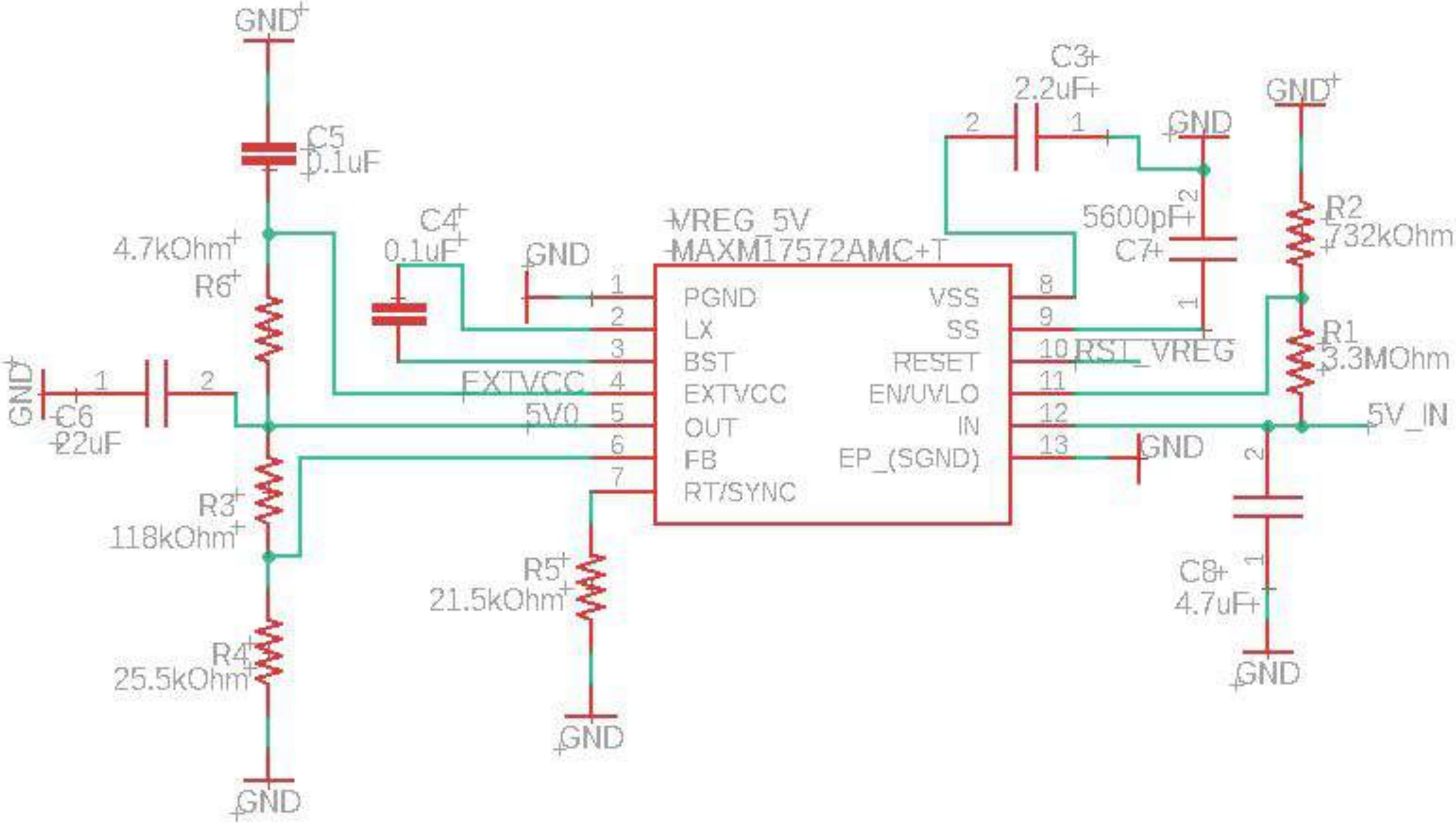
12V SWITCHING BUCK REGULATOR CIRCUIT
IN: 24VDC
OUT: 12VDC 1A

NOTES:
-KEEP FEEDBACK WIRING AWAY FROM INDUCTOR FLUX IN LAYOUT
-KEEP LINES FOR CIN, COUT, SCHOTTKY, AND GND AT MIN LENGTH AND TIED TO GND PLANE

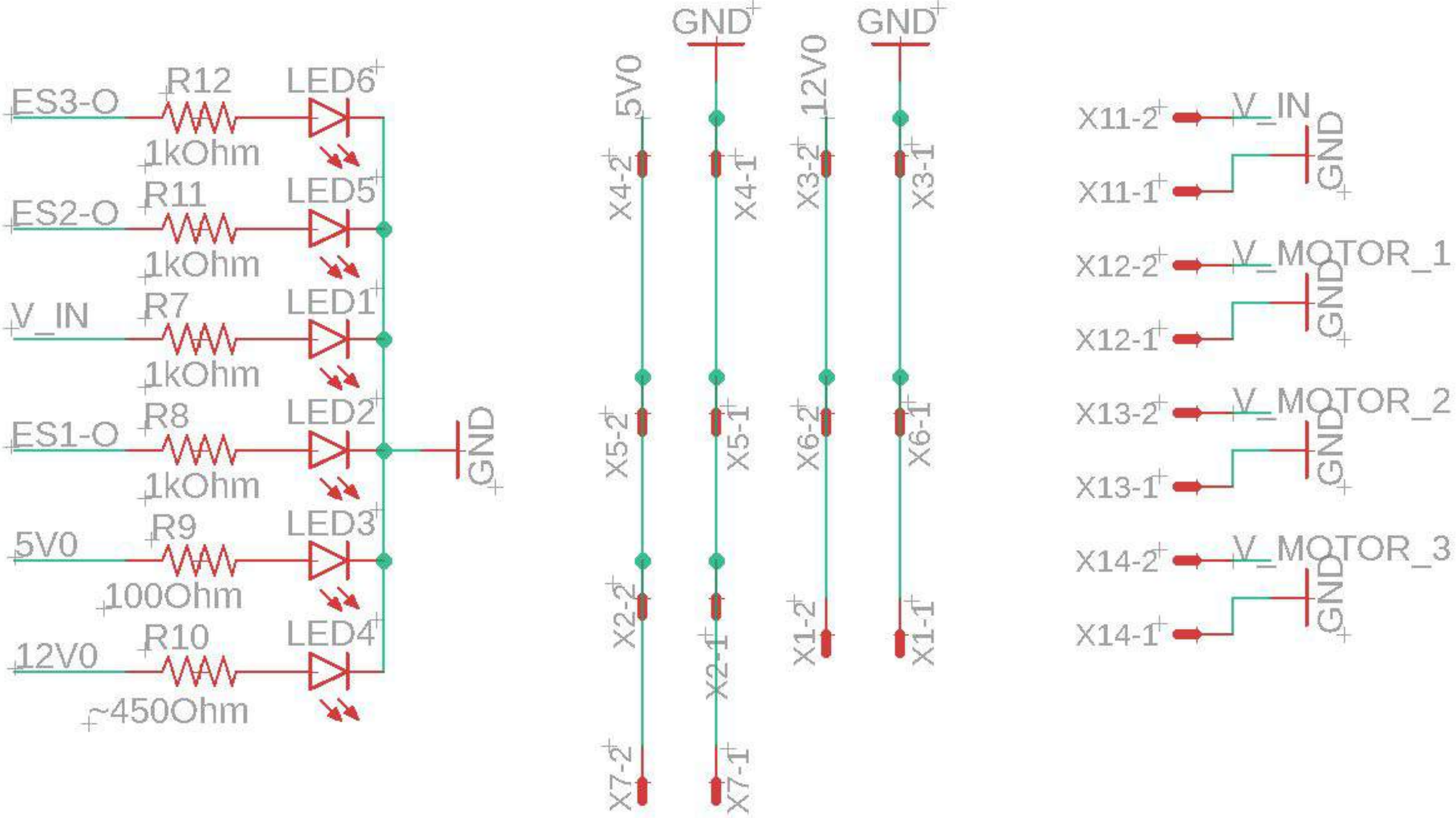
Power Board: 12V Domain



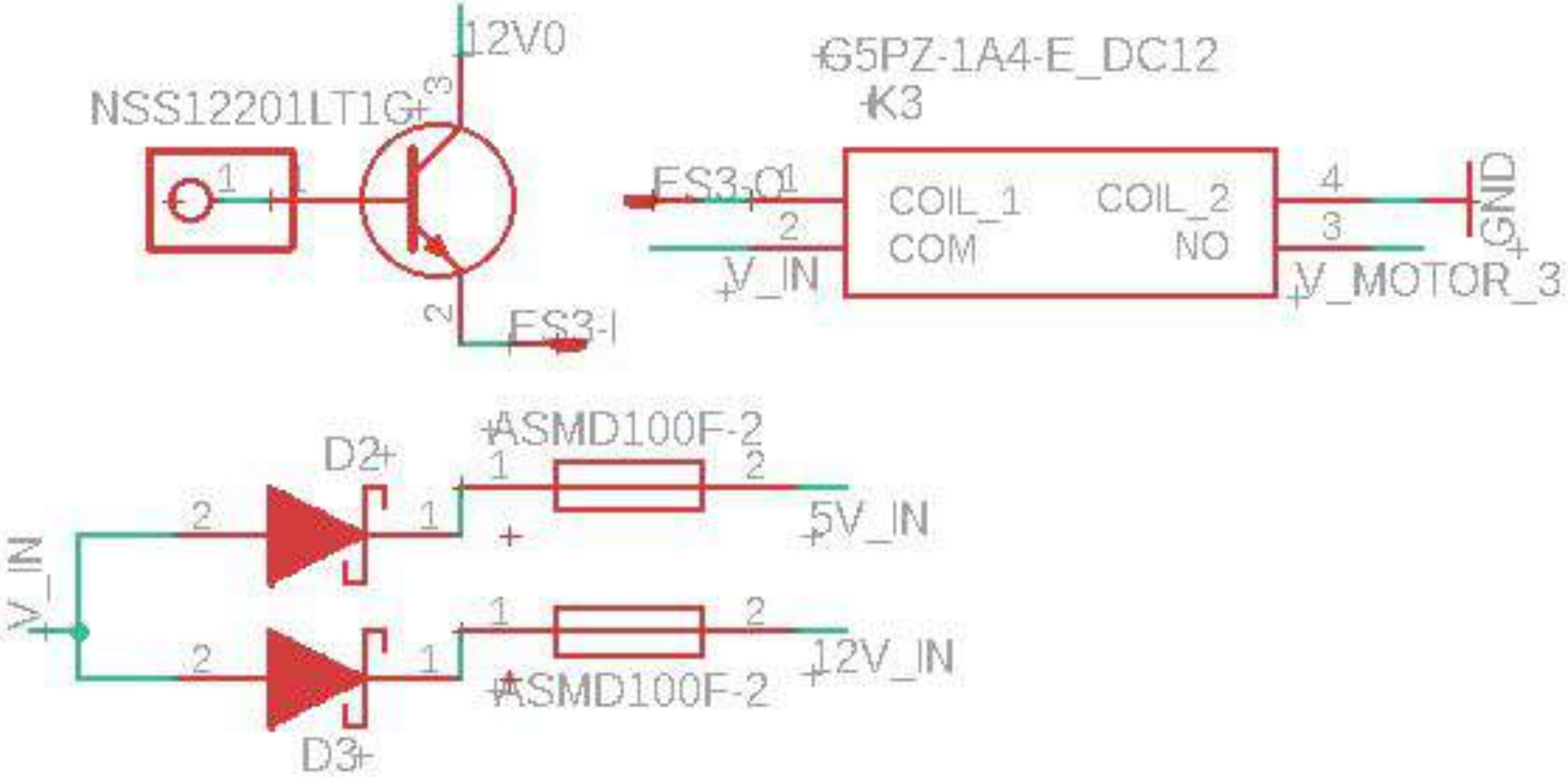
Power Board: 5V Domain



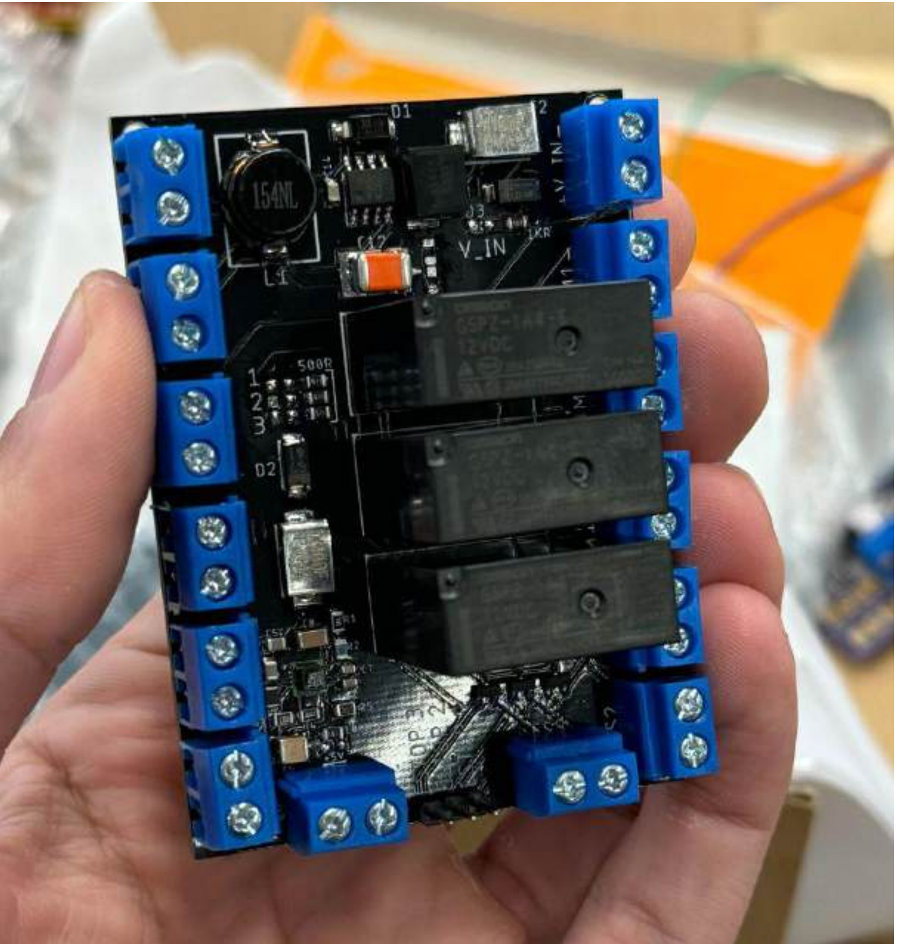
Power Board: Indicators and I/O

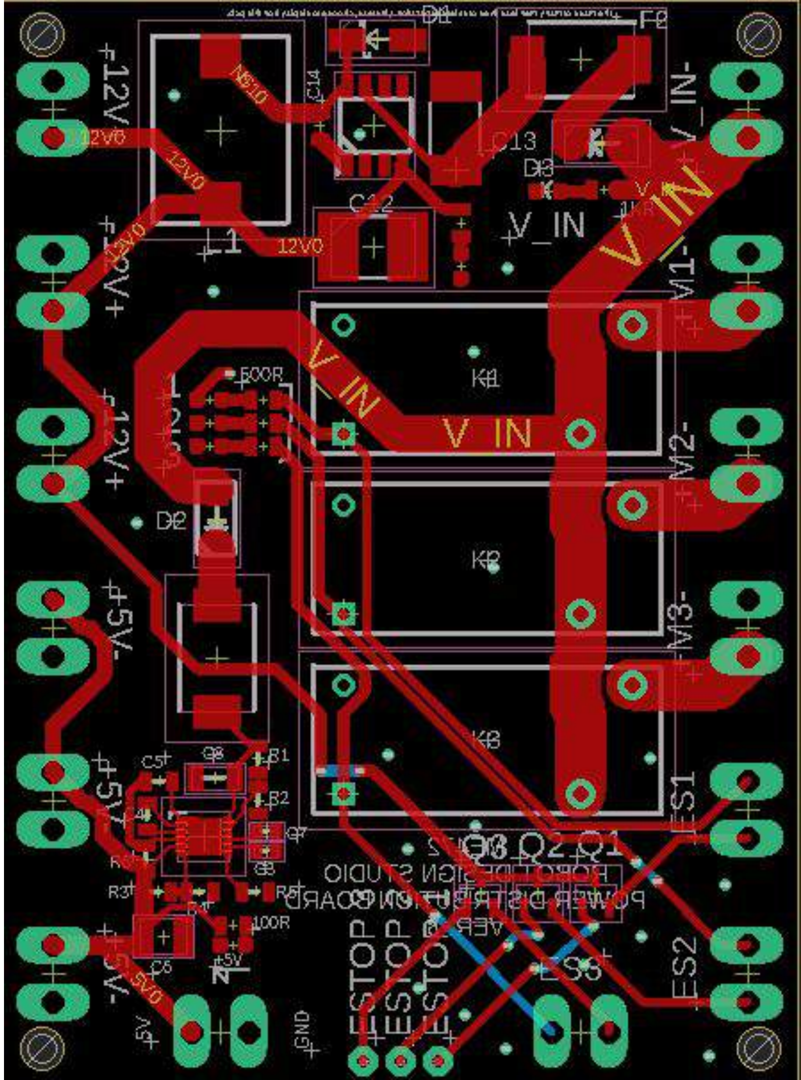


Power Board: Relay Circuit

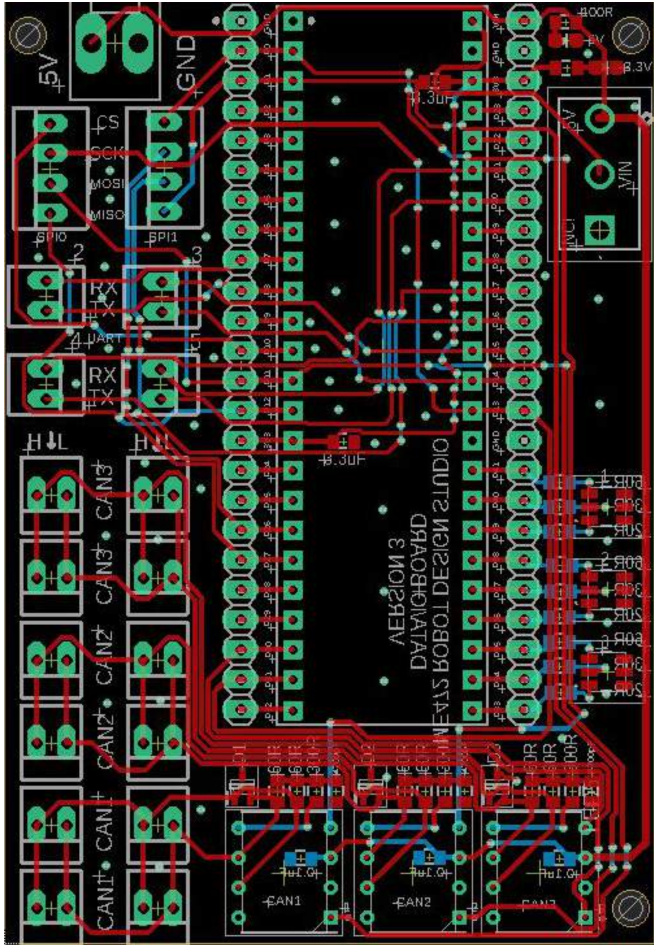


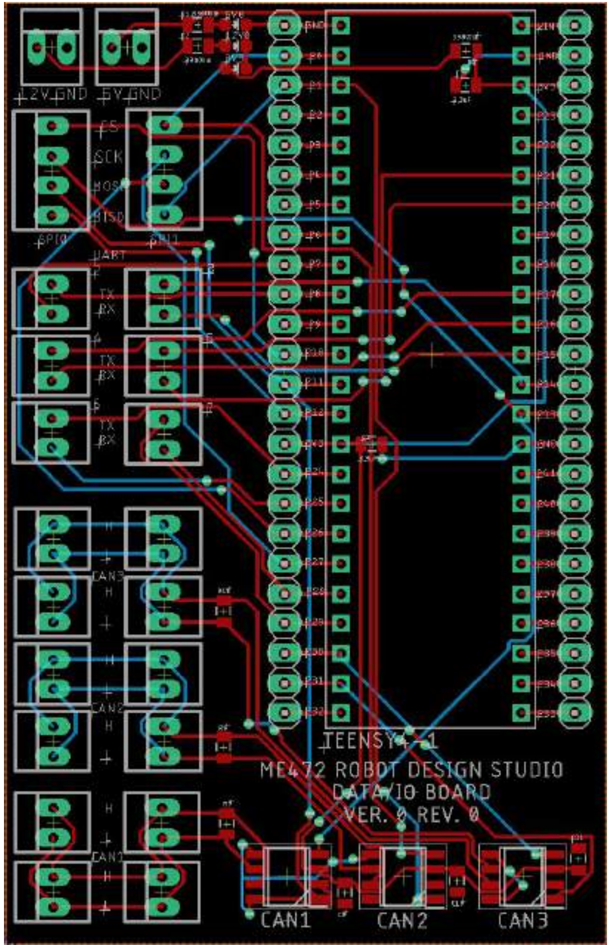
Power Board Layout





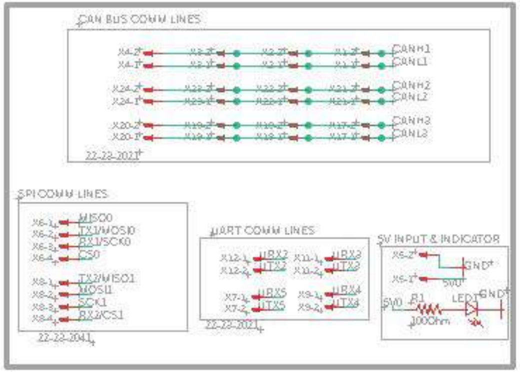
New v.s. Old Data Board





Overall Data Board Schematic

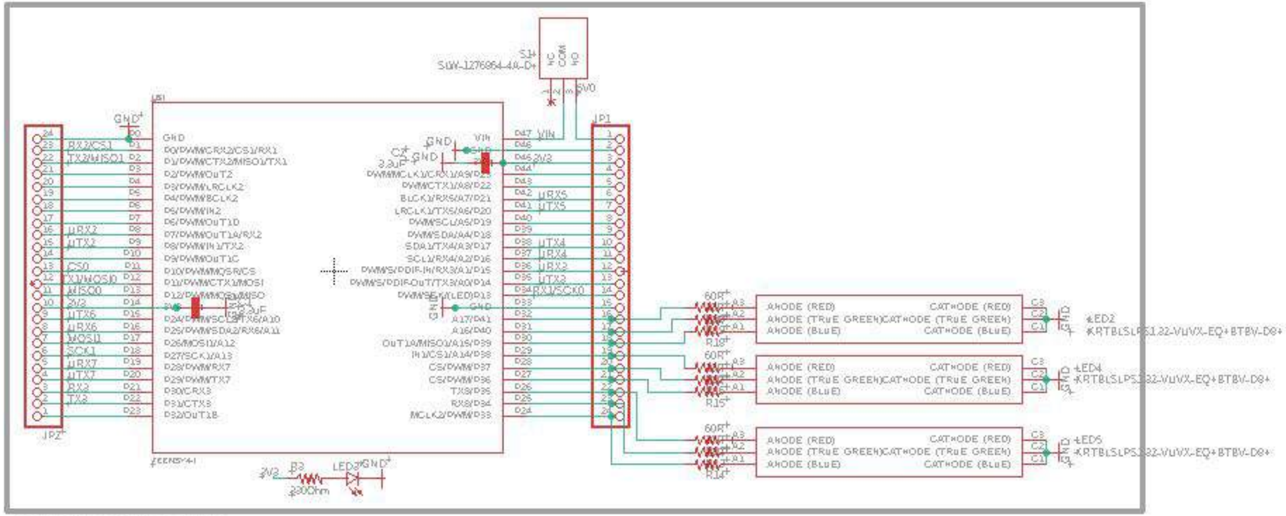
Data IO



TEENSY COMM BUS/POWER CONNECTORS

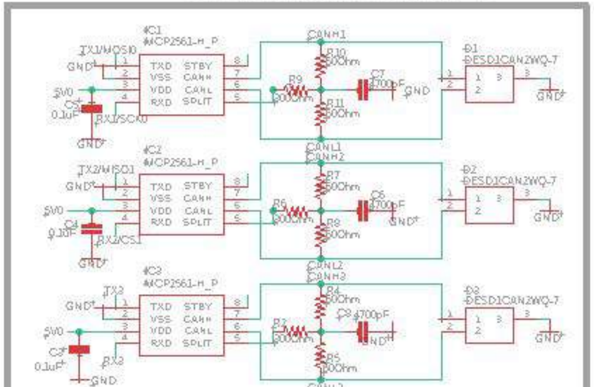
NOTES:
-2.54MM (0.100 IN.) PITCH SPACING USED FOR CONNECTORS
-COMM LINES ARE ALSO ACCESSIBLE AT HEADERS
-CANNOT SIMULTANEOUSLY OPERATE SPI AND CAN BUS.
PROVISION PINS ACCORDINGY ON TEENSY
-UART LINES ARE ISOLATED FROM ALL CAN/SPI CONNECTORS

Teensy



TEENSY 4.1 AND BREAKOUT HEADERS

NOTES:
-PLACE BYPASS CAPACITORS ADJACENT TO PINS
-FEMALE HEADER SOCKETS WILL MOUNT TEENSY TO PCB



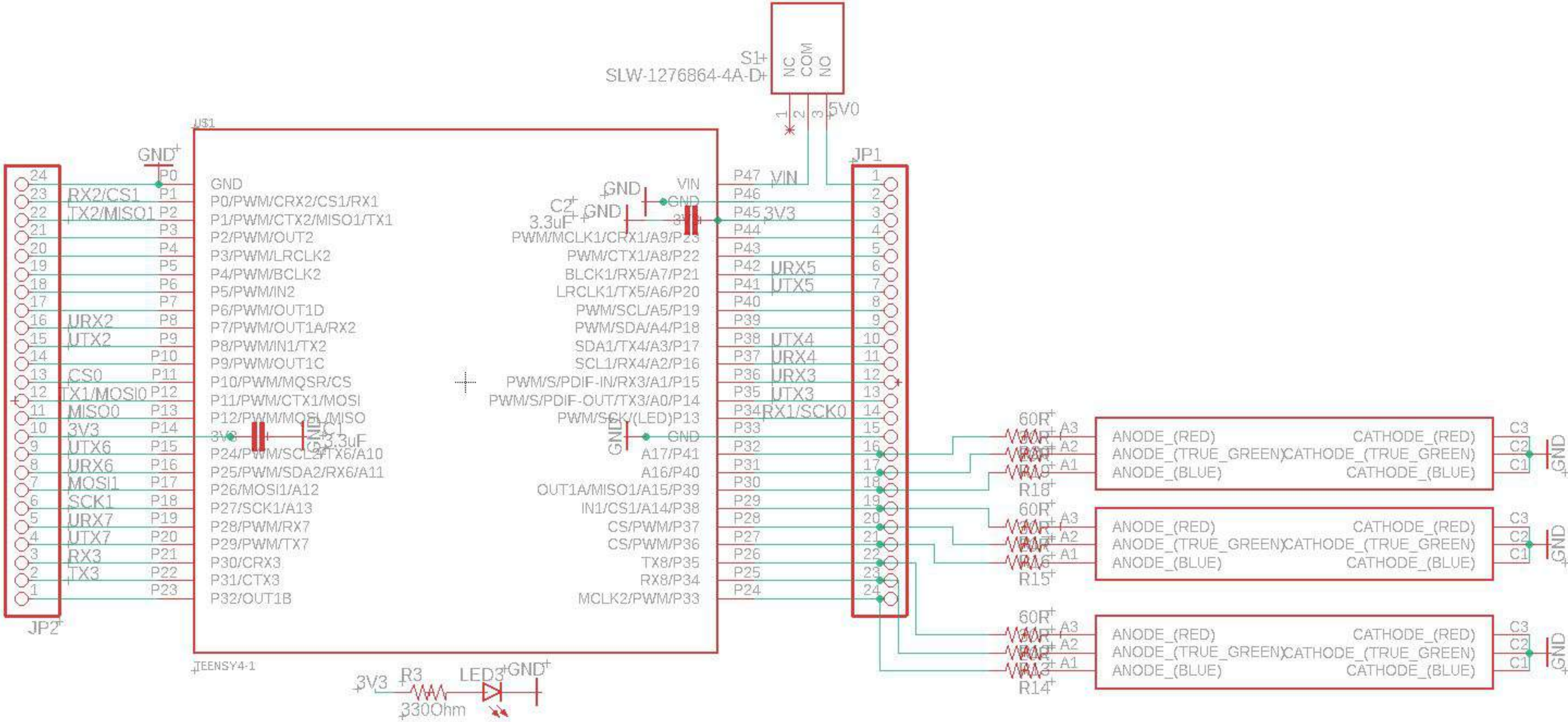
CAN TRANSEIVER CIRCUIT

~~~~~~~~~~~~~~~~~~~~ATTENTION~~~~~~~~~~~~~~~~~~~~
A SECOND 120Ohm RESISTOR IS REQUIRED IN PARALLEL AT END
OF CAN BUS. THIS TERMINATION RESISTOR IS NECESSARY TO BRING
BUS IMPEDANCE TO 120Ohm
~~~~~~

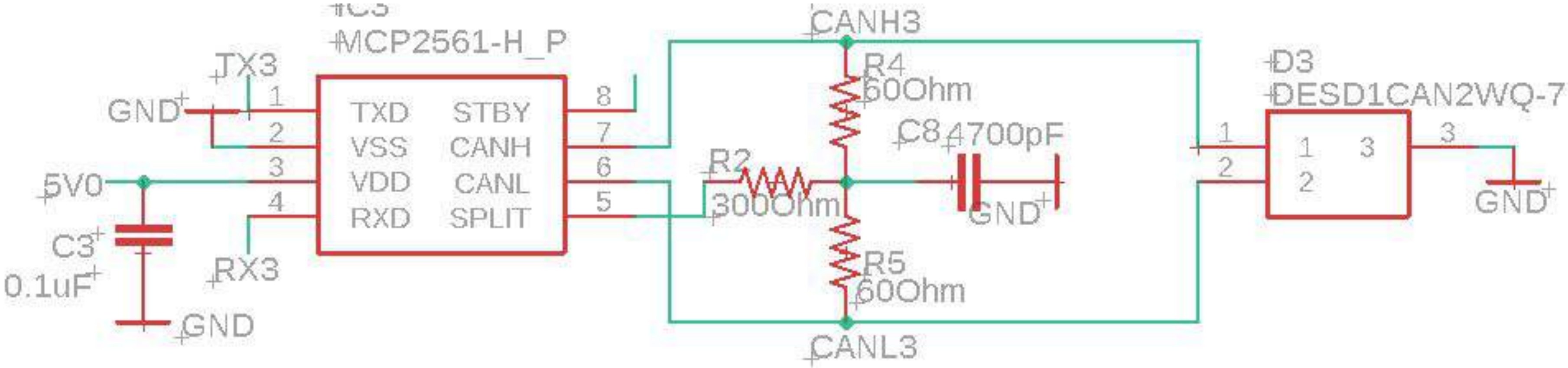
NOTES:
-THREE SEPARATE BUSSES
-CANNOT SIMULTANEOUSLY OPERATE CAN BUS AND SPI PINS.
MUST CONFIGURE ON TEENSY
-CAN BUS GND MUST BE TIED TO LOGIC LEVEL GND

CAN Transceiver

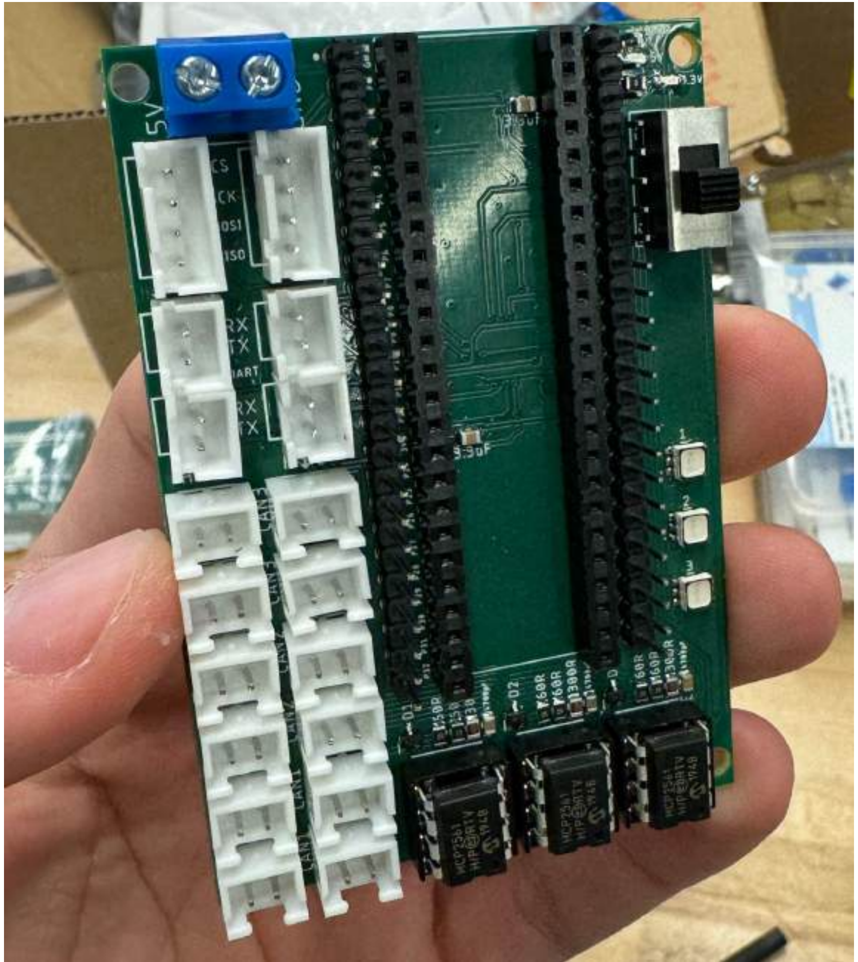
Data Board - Teensy Circuit

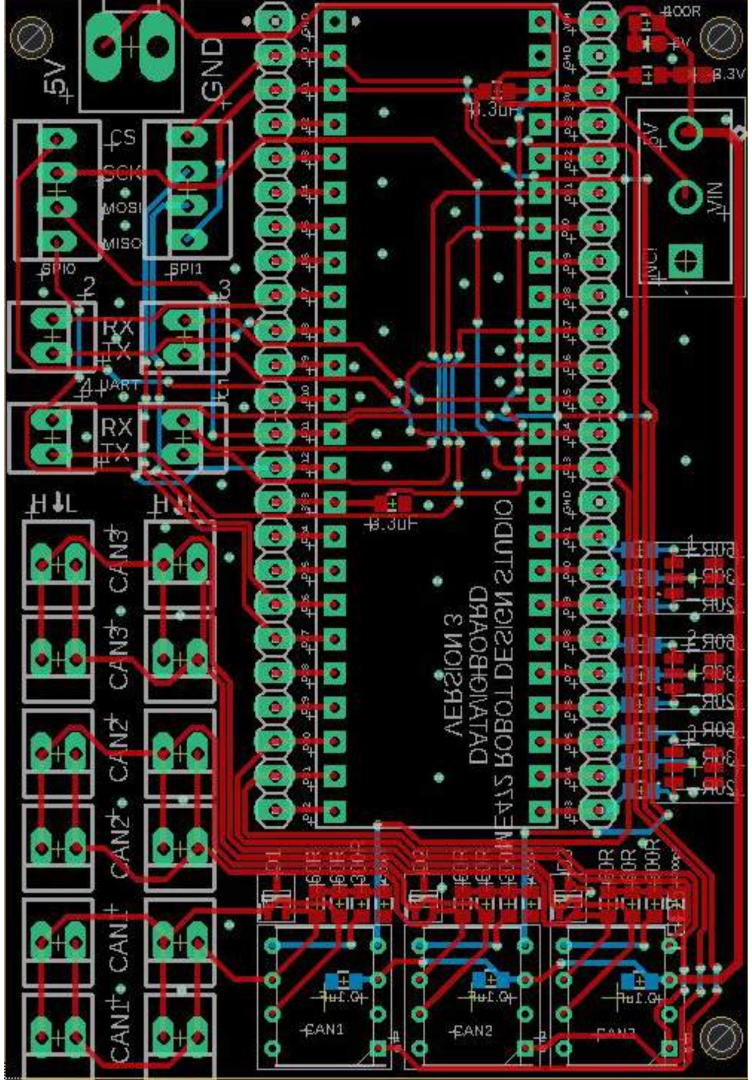


Data Board - CAN Transceiver Circuit



Data Board Layout

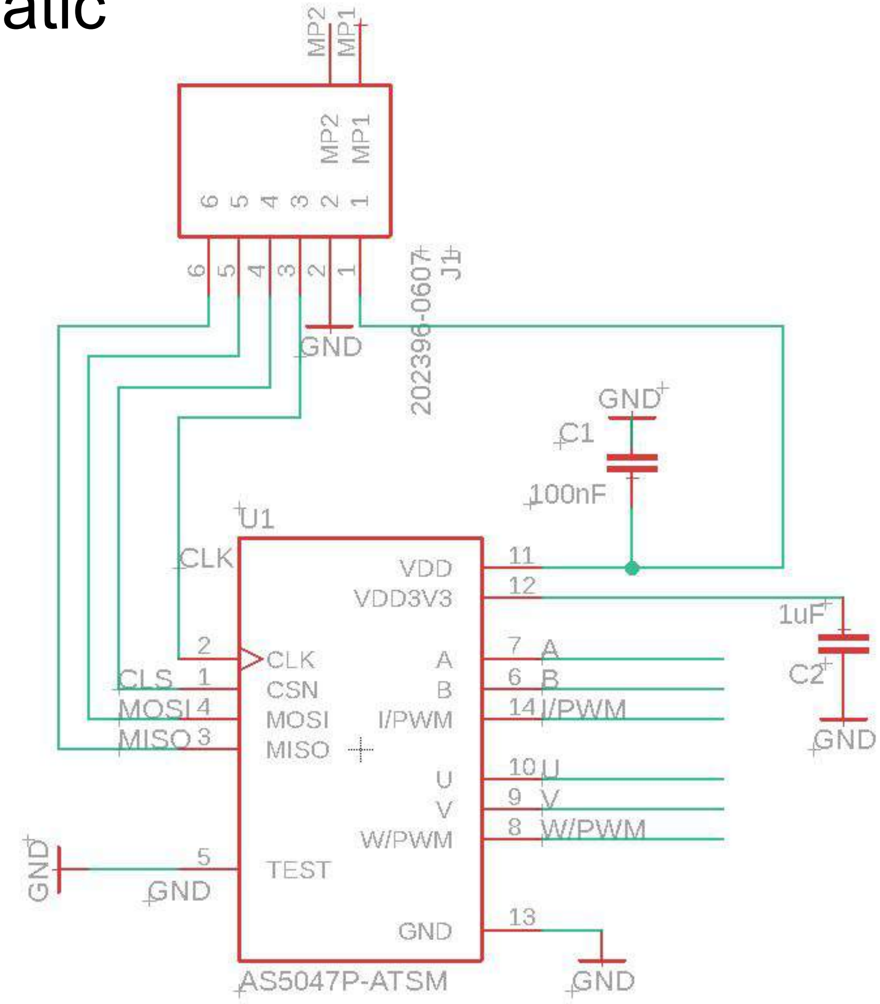




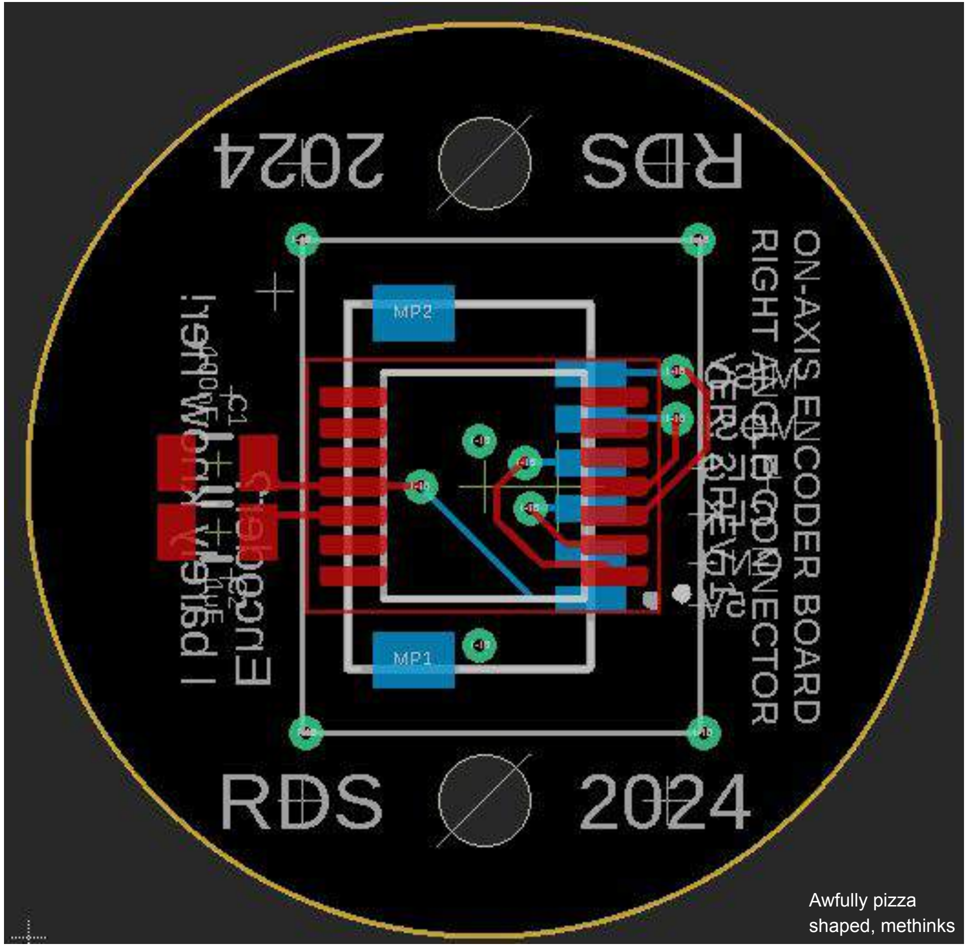
Encoder Boards

Truly some of THE electronics of all time

Encoder Board Schematic

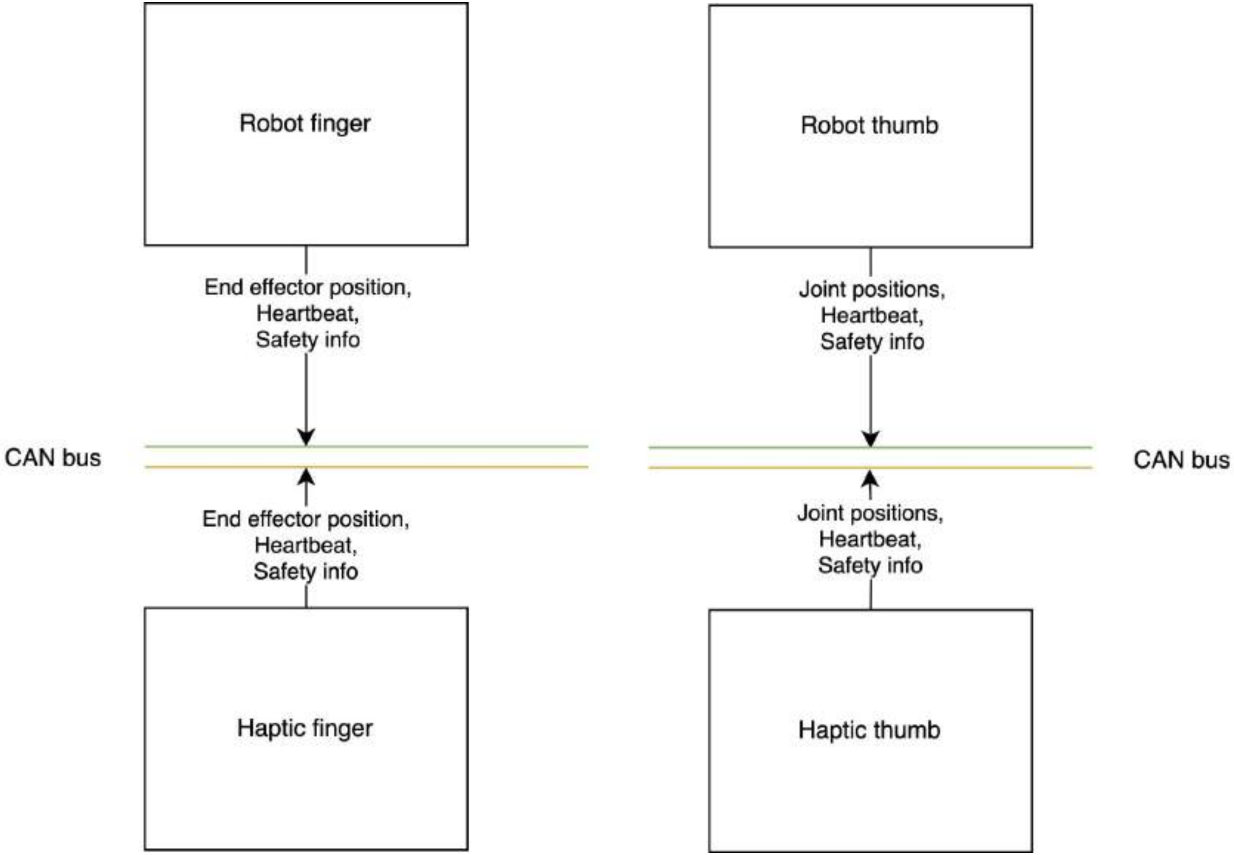


Encoder Board Schematic

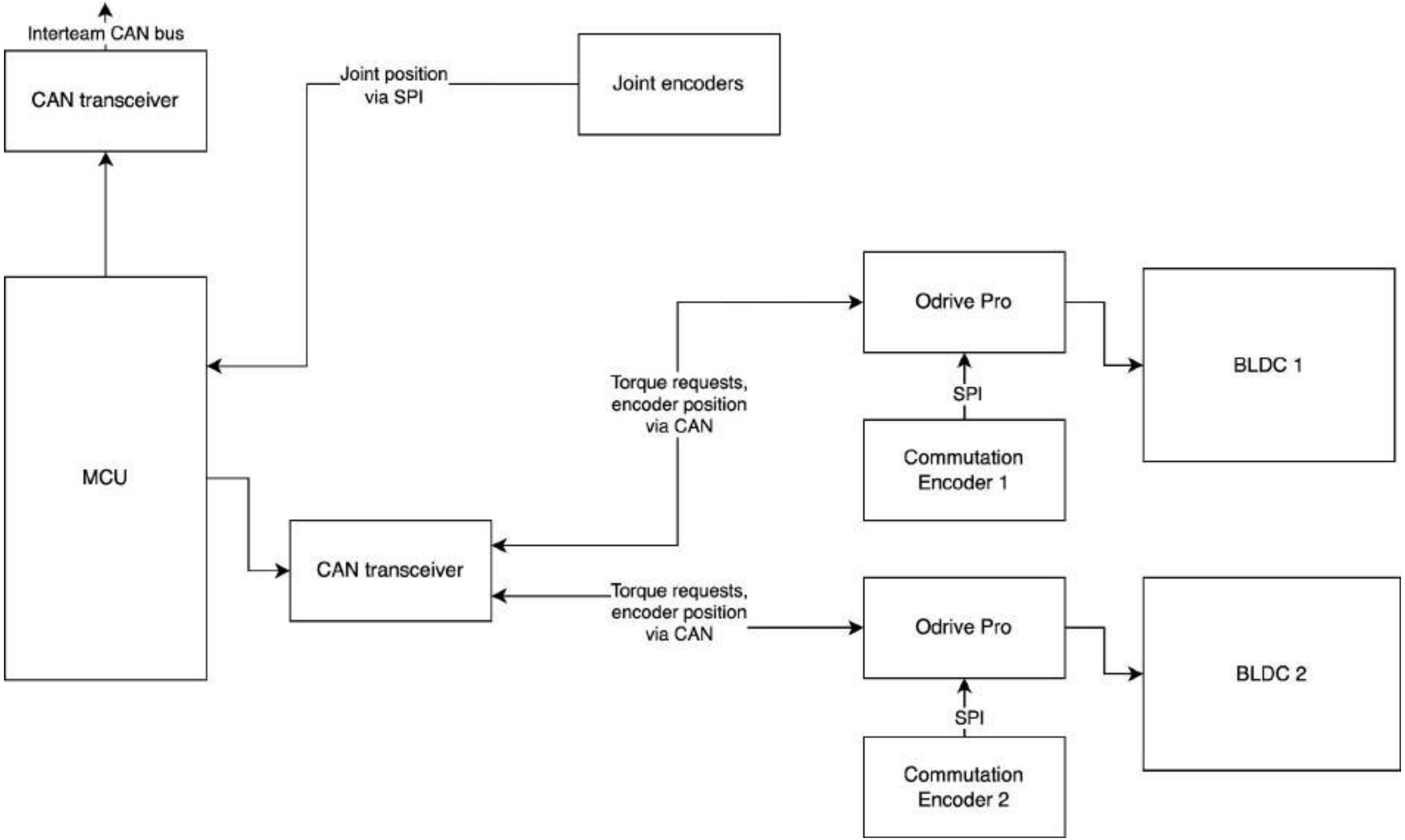


Awfully pizza shaped, methinks

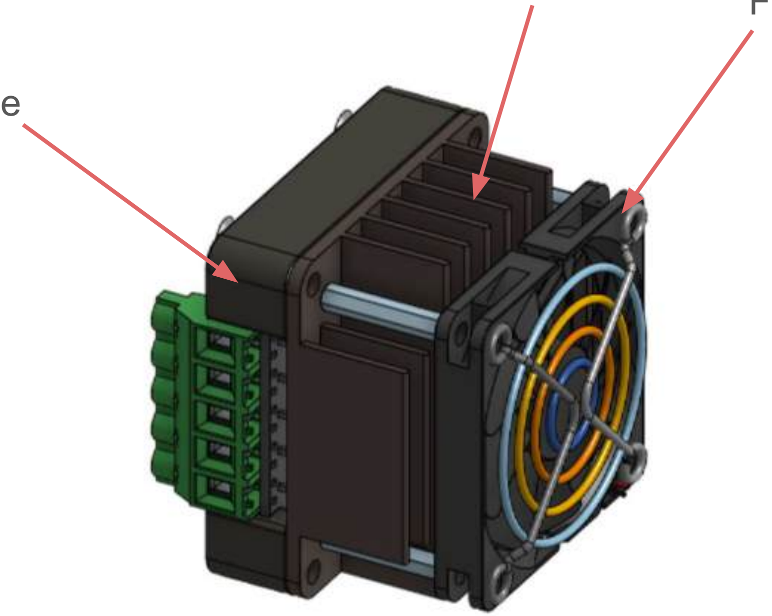
High Level Communications: Interteam

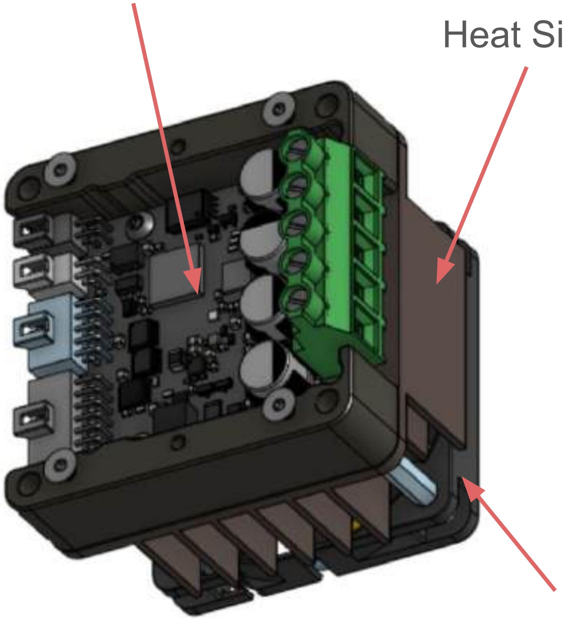


High Level Communications: Intrateam

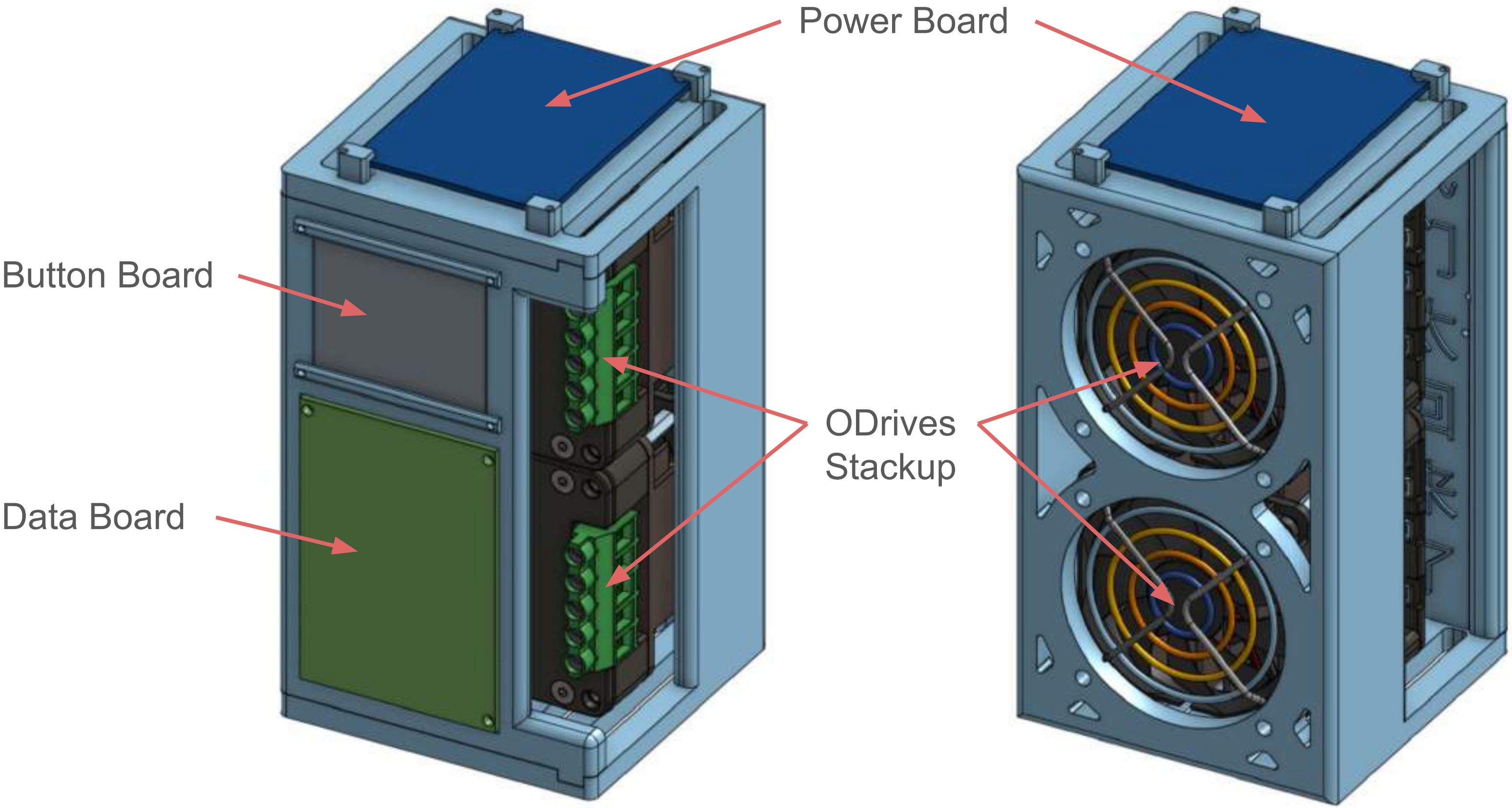


ODrive Stackup



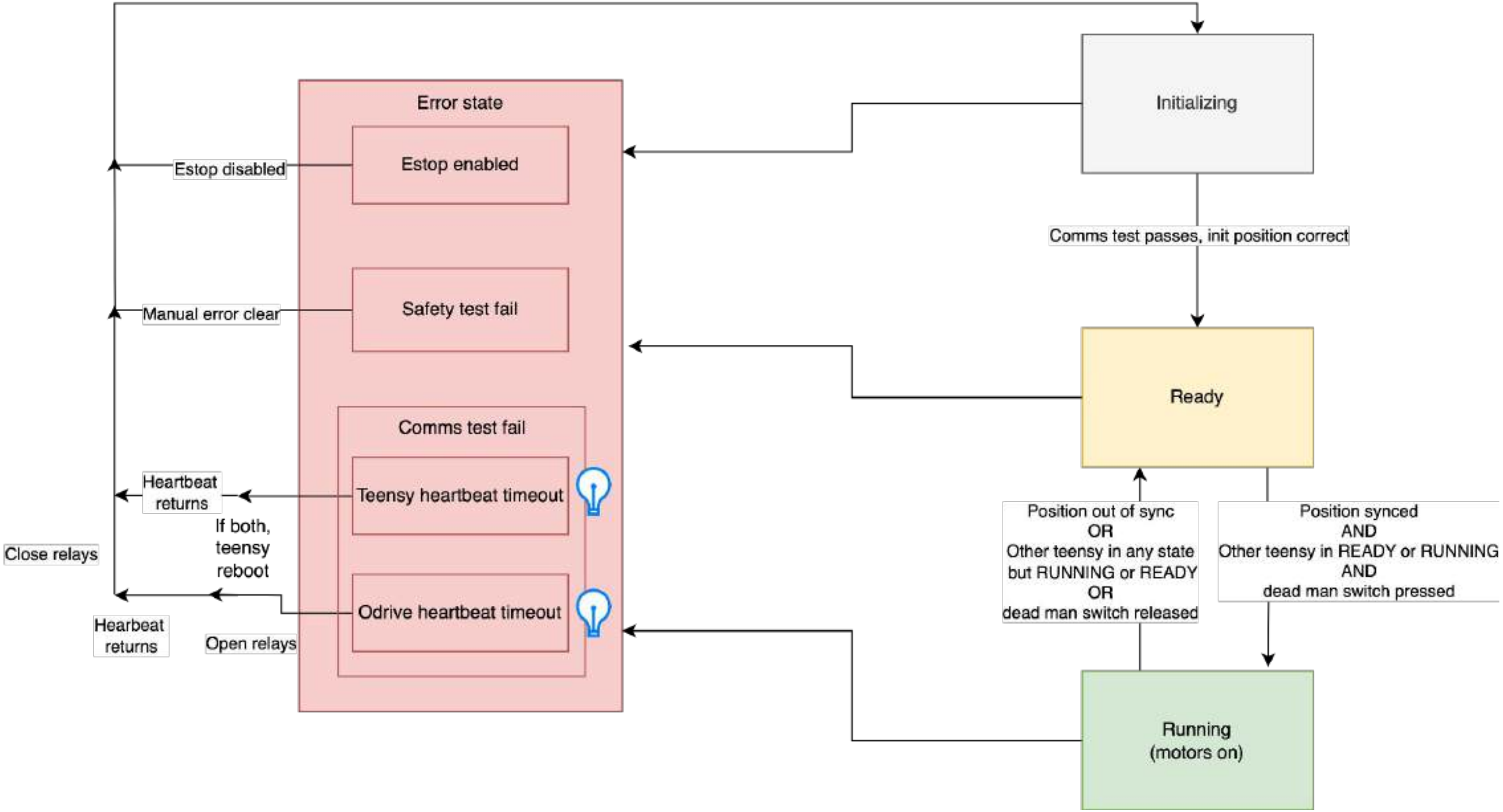


Electronic Box aka “the Fridge”

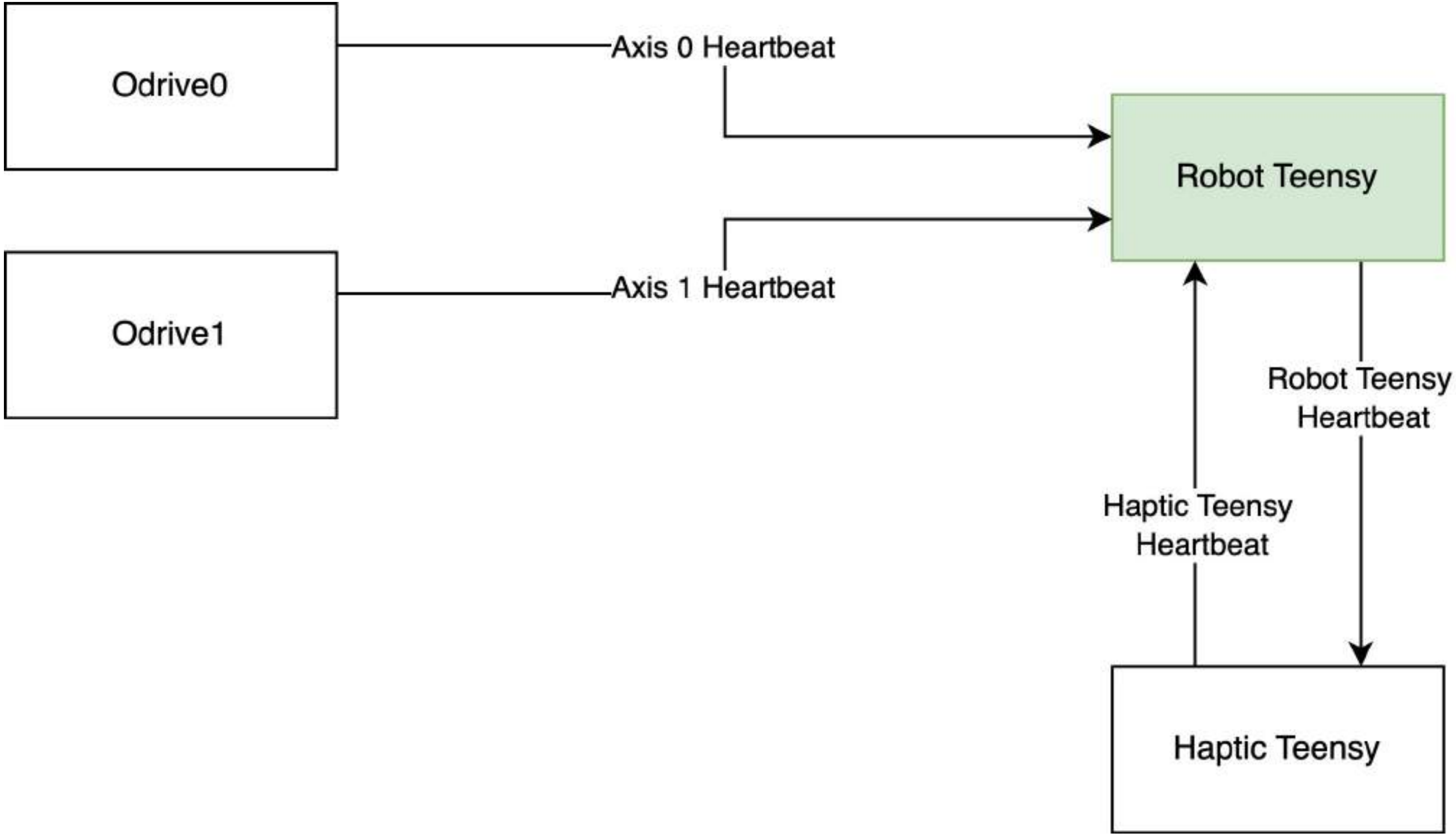


Startup

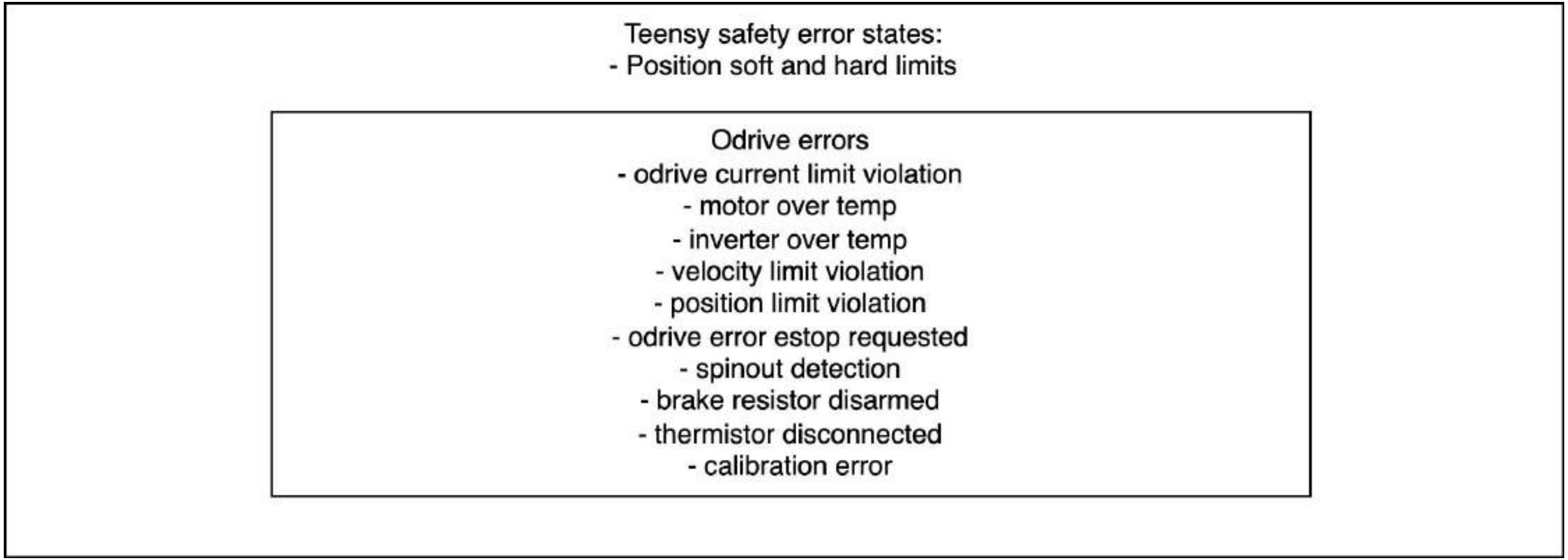
State Diagram



Communication Test



Safety Test

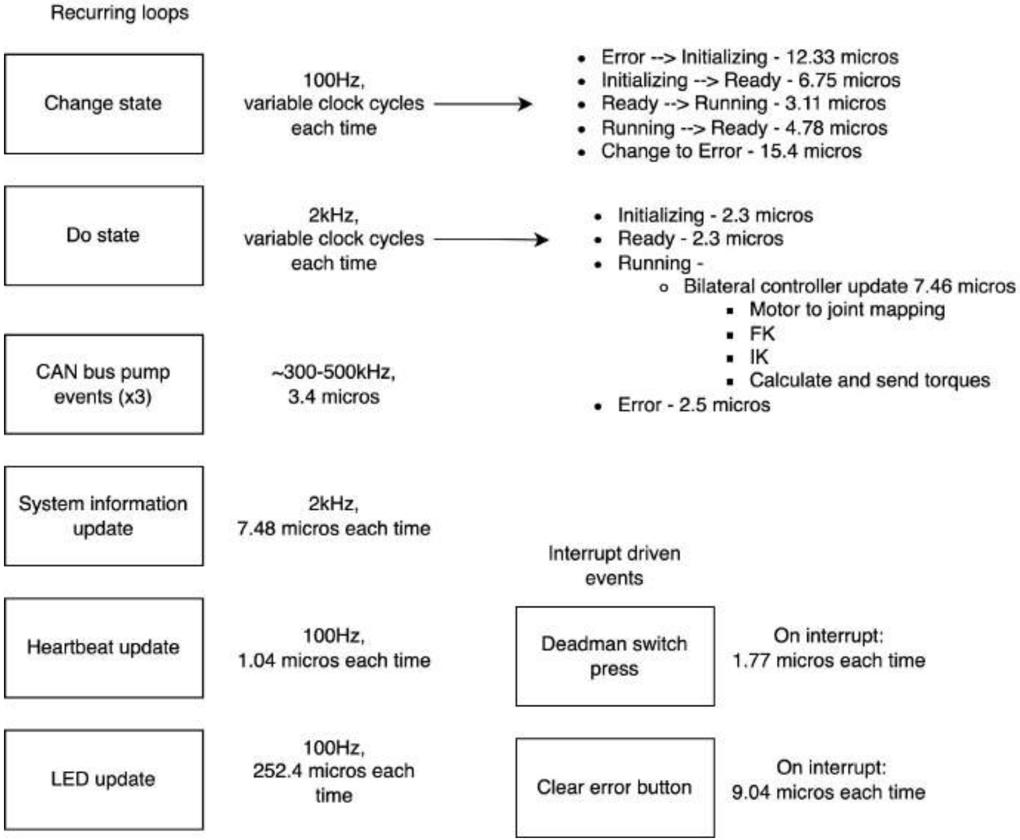


Teensy safety error states:
- Position soft and hard limits

Odrive errors
- odrive current limit violation
- motor over temp
- inverter over temp
- velocity limit violation
- position limit violation
- odrive error estop requested
- spinout detection
- brake resistor disarmed
- thermistor disconnected
- calibration error

Control

System Control Loop



Recurring loops

Change state
100Hz, variable clock cycles each time →

- Error --> Initializing - 12.33 micros
- Initializing --> Ready - 6.75 micros
- Ready --> Running - 3.11 micros
- Running --> Ready - 4.78 micros
- Change to Error - 15.4 micros

Do state
2kHz, variable clock cycles each time →

- Initializing - 2.3 micros
- Ready - 2.3 micros
- Running -
  - Bilateral controller update 7.46 micros
    - Motor to joint mapping
    - FK
    - IK
    - Calculate and send torques
- Error - 2.5 micros

CAN bus pump events (x3)
~300-500kHz, 3.4 micros

System information update
2kHz, 7.48 micros each time

Heartbeat update
100Hz, 1.04 micros each time

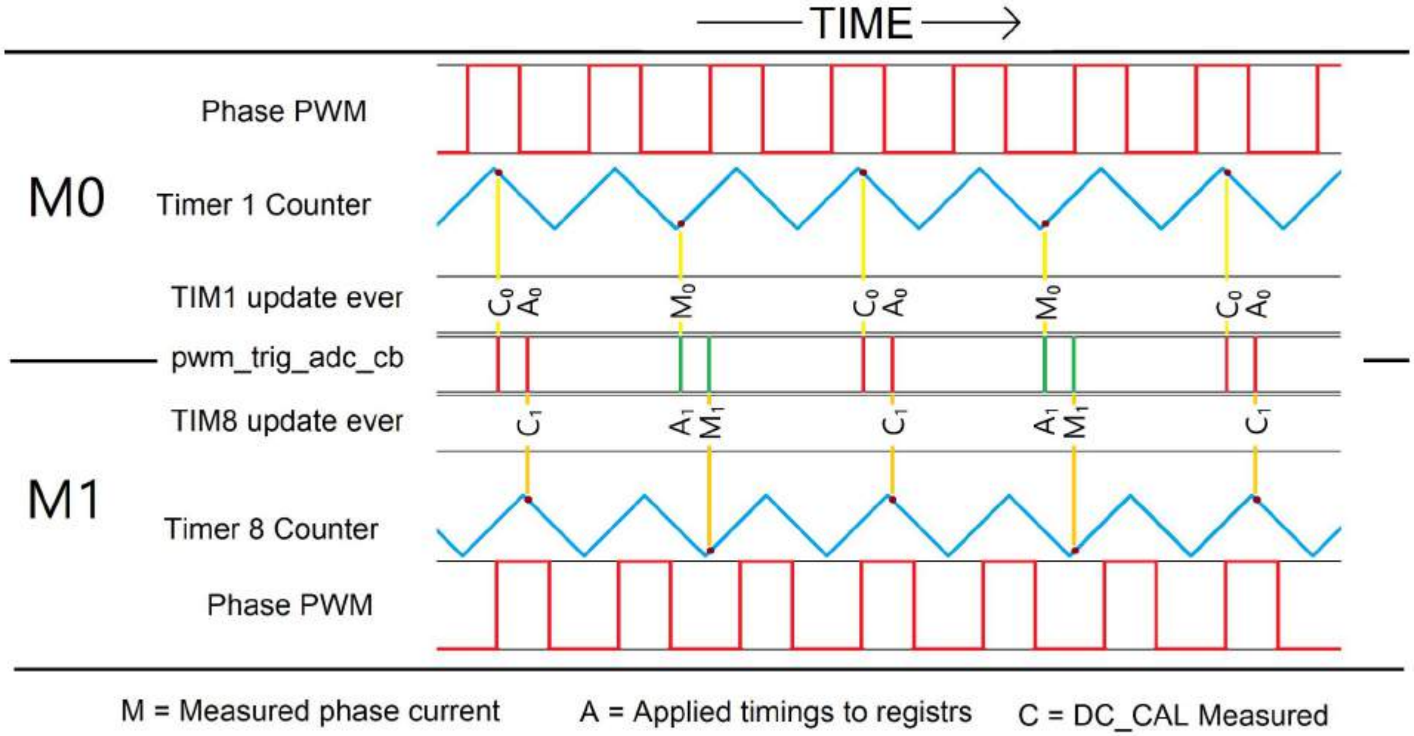
LED update
100Hz, 252.4 micros each time

Interrupt driven events

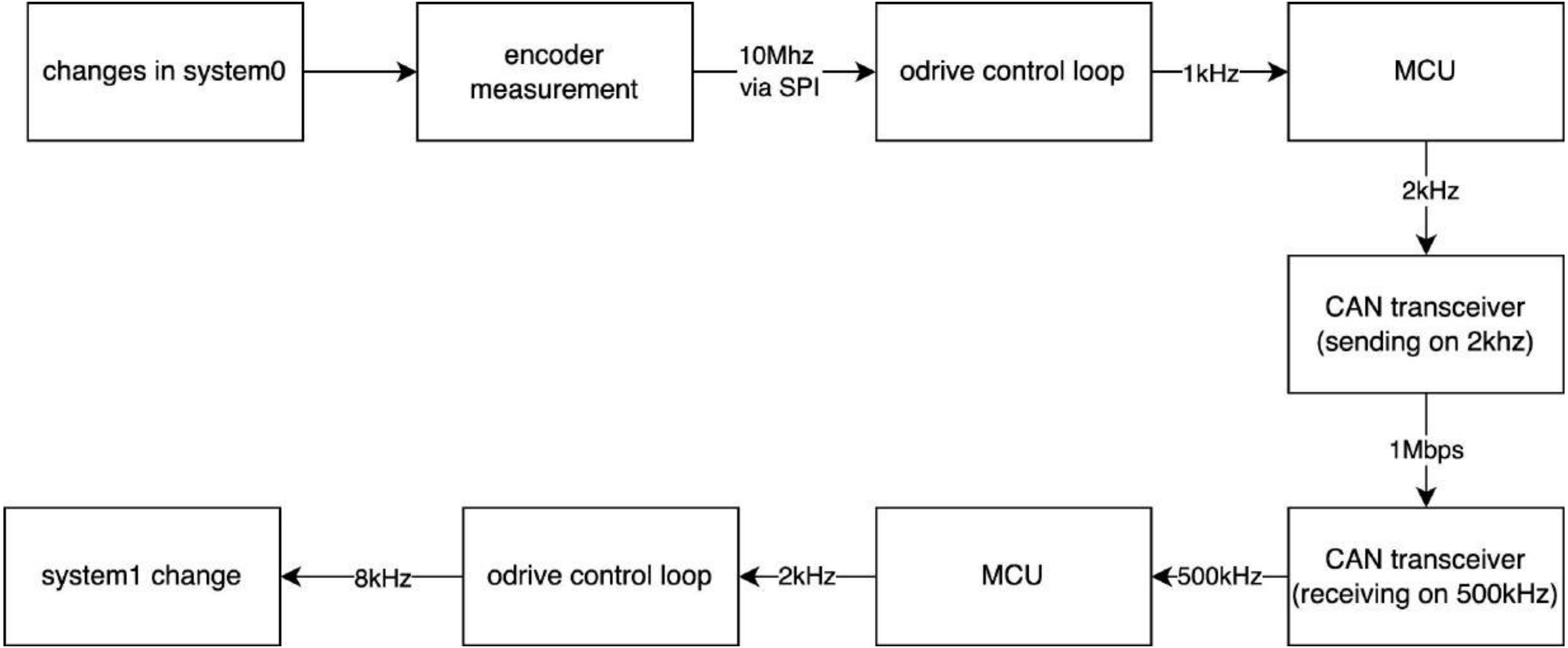
Deadman switch press
On interrupt: 1.77 micros each time

Clear error button
On interrupt: 9.04 micros each time

ODrive Control Loop



Full System Timing



changes in system0

encoder measurement

10Mhz via SPI

odrive control loop

1kHz

MCU

2kHz

CAN transceiver (sending on 2khz)

1Mbps

CAN transceiver (receiving on 500kHz)

500kHz

MCU

2kHz

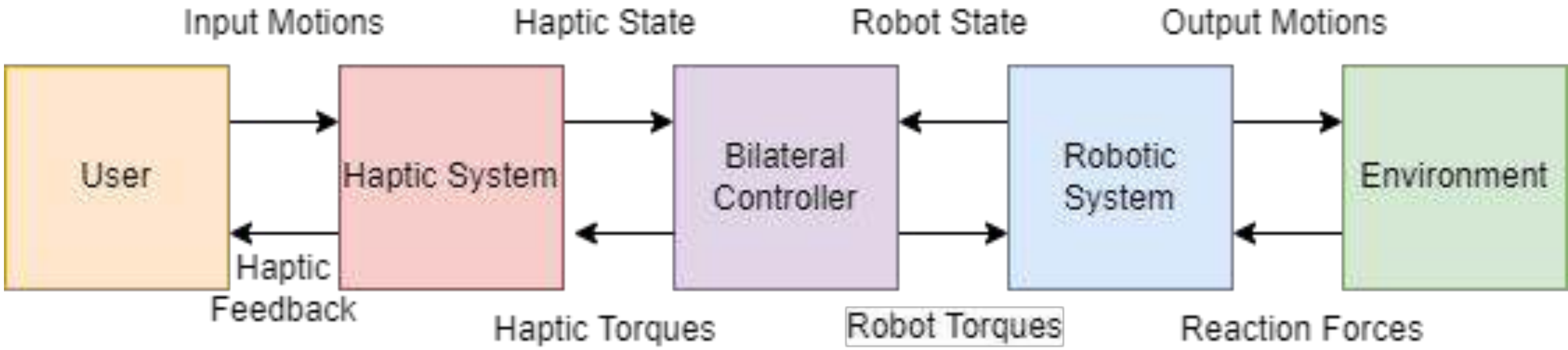
odrive control loop

8kHz

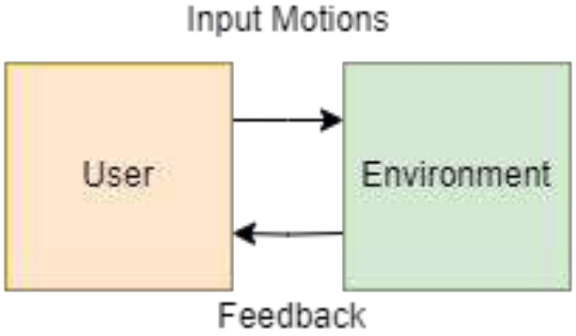
system1 change

Bilateral Control Concepts

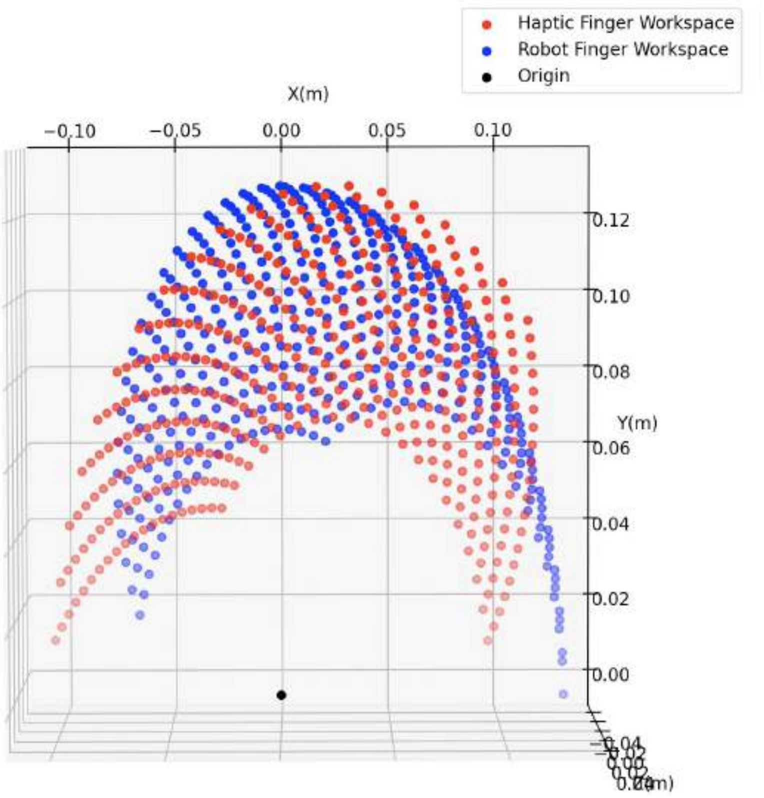
Control Structure



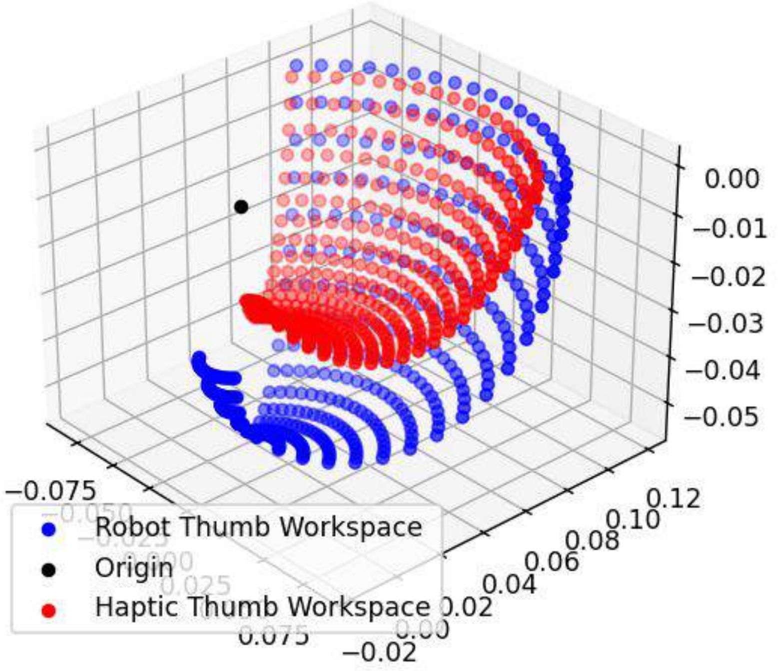
Ideal Bilateral Controller:



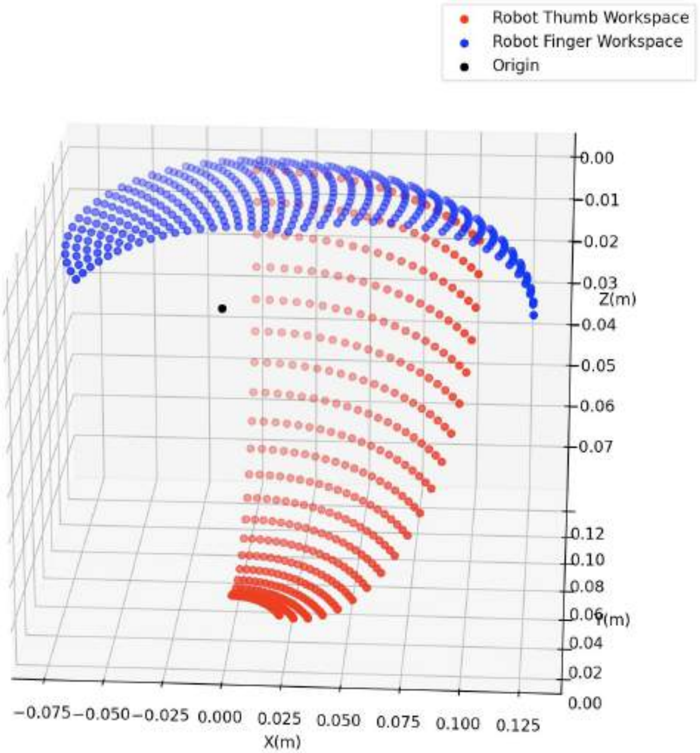
Finger Systems



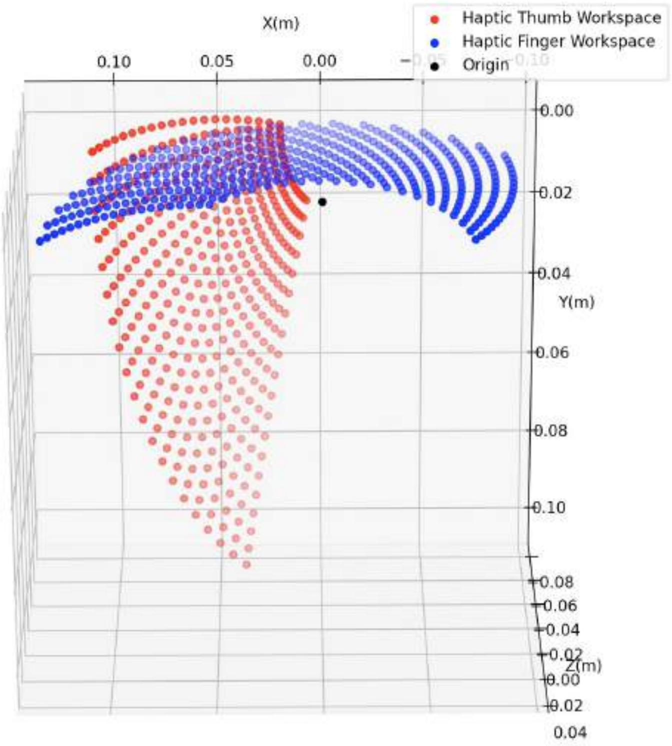
Thumb Systems



Robot System



Haptic System



Mapping

- Each system only communicates with its dual
    - Ie robot finger depends only on haptic finger
- Finger Mapping occurs between end effector positions
- Thumb Mapping occurs between joint positions

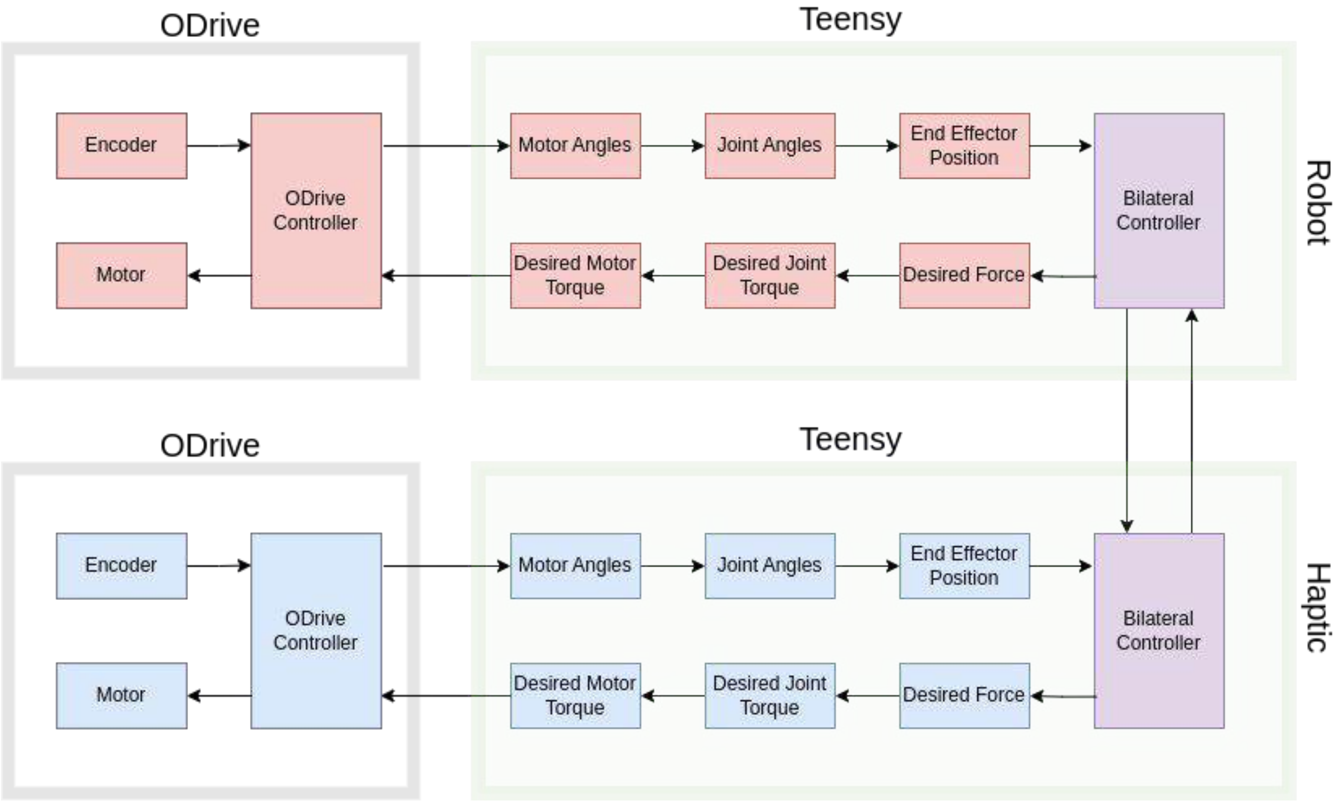
Finger mapping

- Assuming DIP is common origin
- Perfect mapping is possible in a plane due to the 2D positional workspace
- End effectors are connected with a virtual spring-damper

Thumb mapping

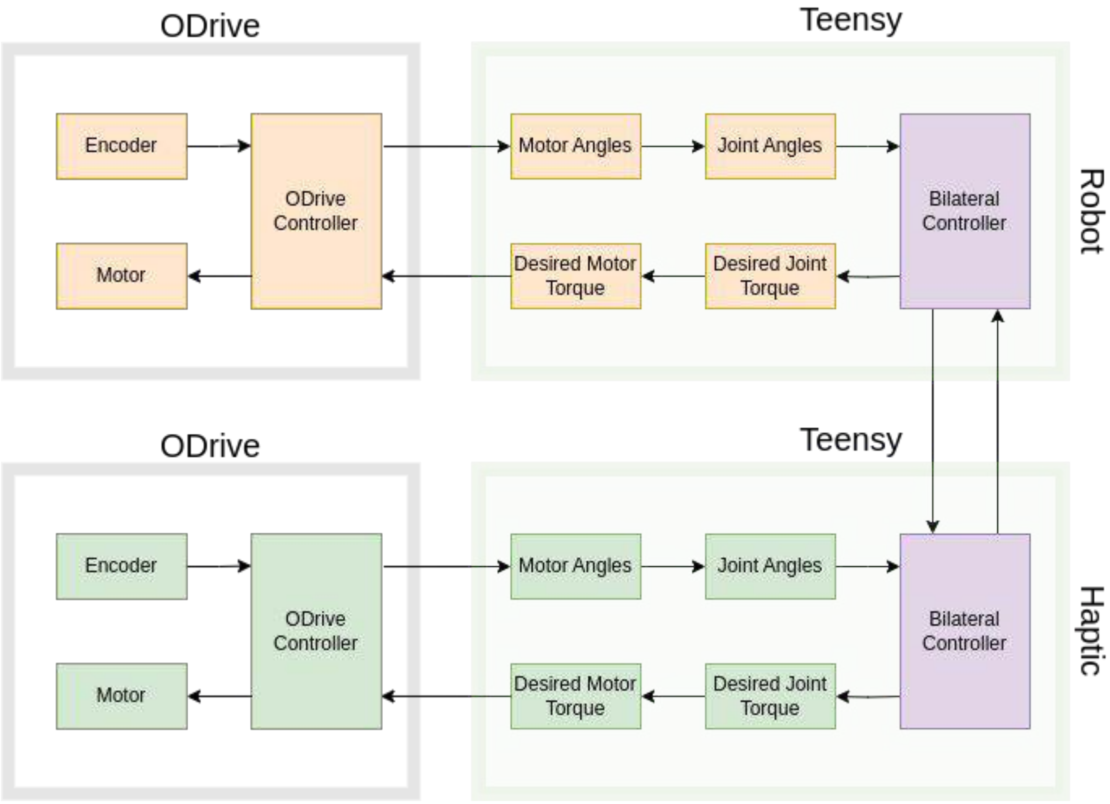
- 3D workspace and kinematic differences between the two interfaces prevents a perfect mapping between the two sides
  - Compensate by matching the joint angles as closely as possible
- Joints are connected by a virtual spring-damper
  - CMC and MCP, not DIP

Bilateral Controller: Finger Control

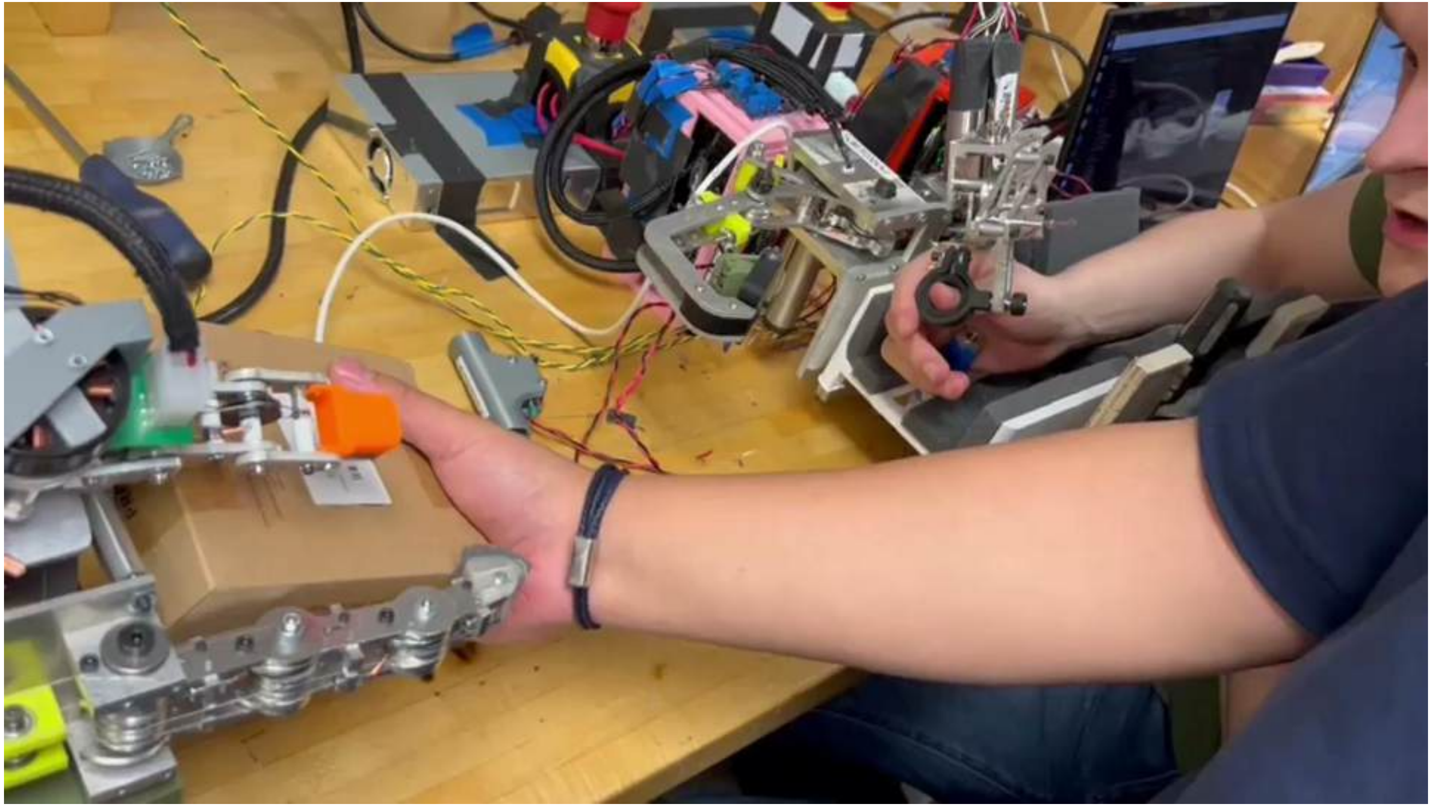


Finger Operation

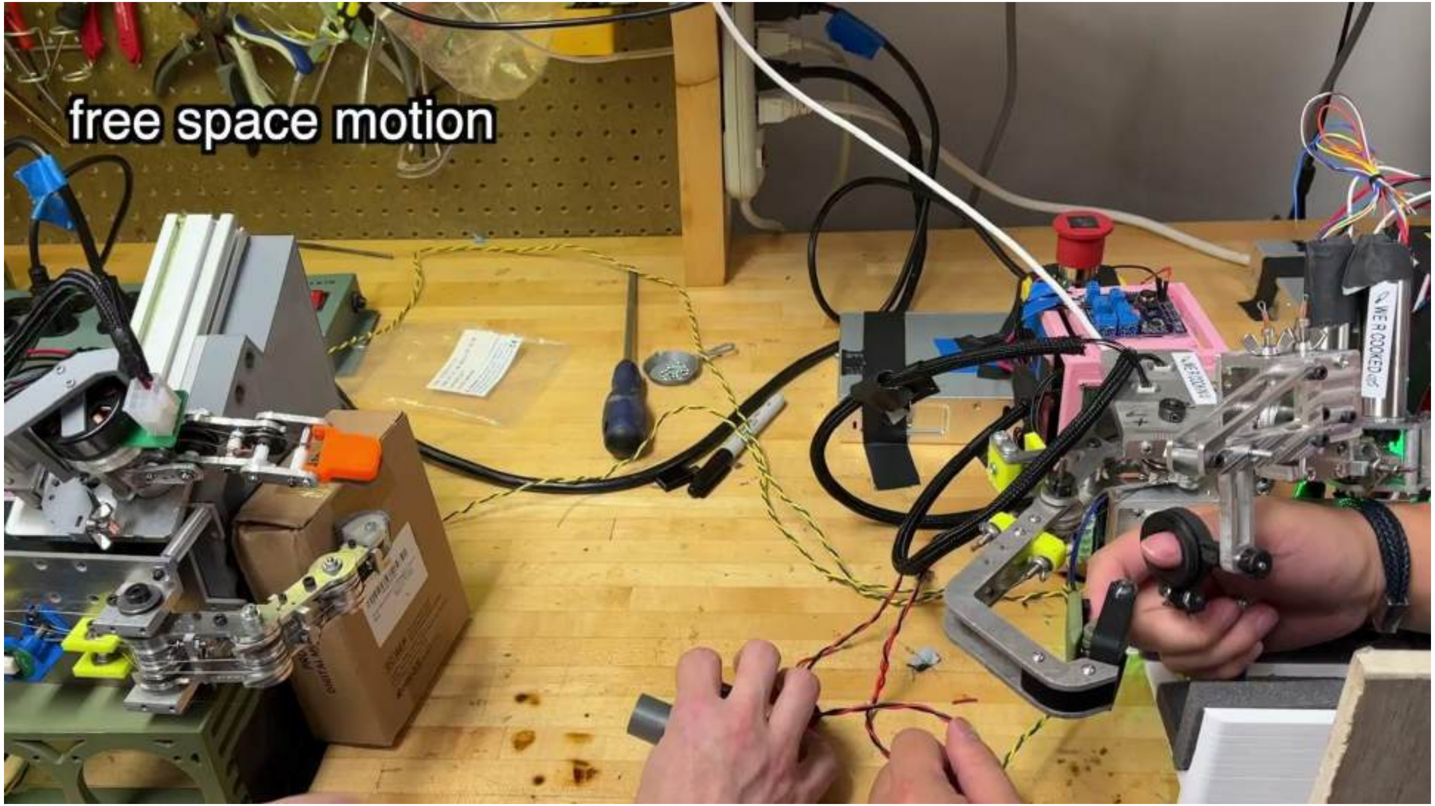
Bilateral Controller: Thumb Control



Thumb Operation



Bilateral Control: Video



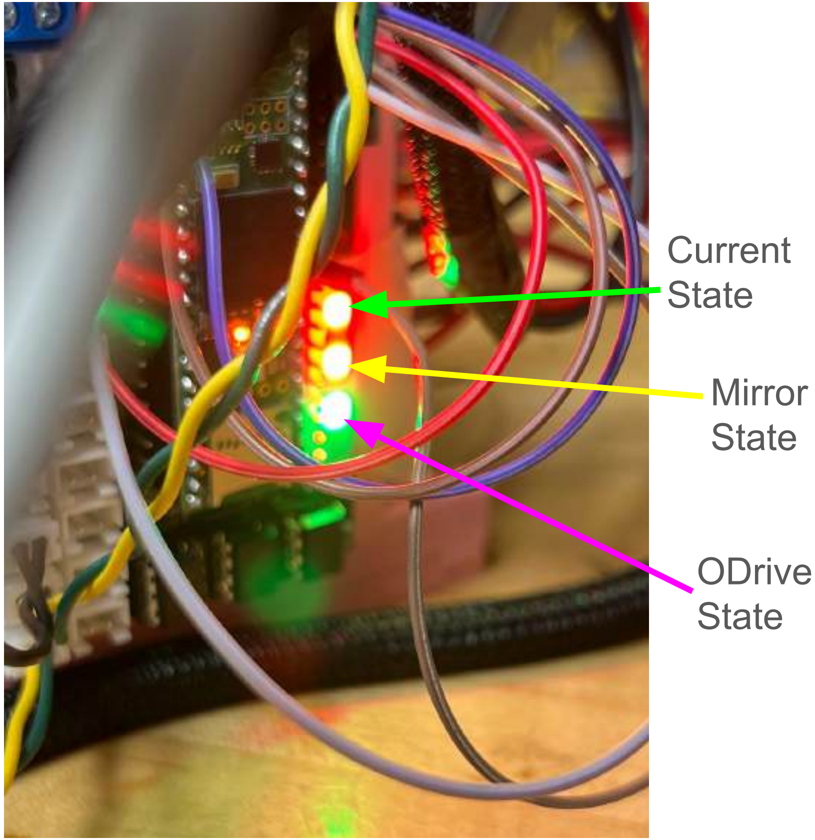
Safety

Hardware Safety

- Dead man’s switch
- Voluntary clear errors button
- E-stop
- Status LEDs
- Connectors that fit one-way

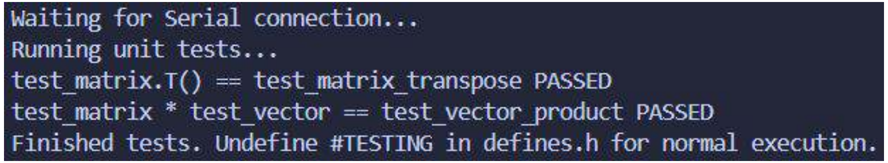
Software Safety

- ODrive-level torque and velocity limits
- Command-level torque limit
- Control state matching
- Required position synchronization
- Joint Limit Avoidance
- Communication timeouts
  - Between systems and with ODrives
- E-stop detection
- Built-in ODrive errors
  - Current limit, encoder disconnect, etc.

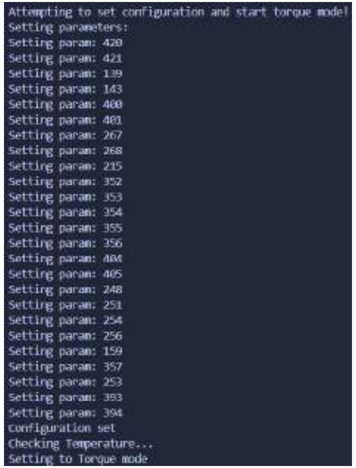


Observability and tooling

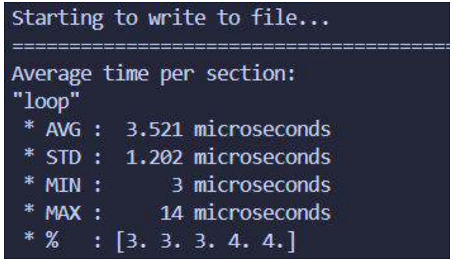
- Status LEDs
- Visualization from serial
- On-board unit testing
- Performance profiler
- Repeatable controller configuration
- Can sniffer with DBC



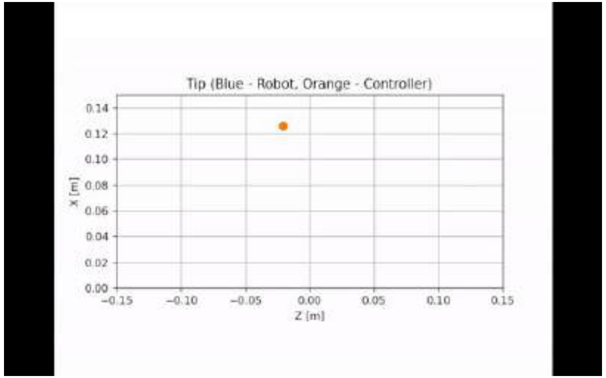
```
Waiting for Serial connection...
Running unit tests...
test_matrix.T() == test_matrix_transpose PASSED
test_matrix * test_vector == test_vector_product PASSED
Finished tests. Undefine #TESTING in defines.h for normal execution.
```



```
Attempting to set configuration and start torque model
Setting parameters:
Setting param: 420
Setting param: 421
Setting param: 139
Setting param: 143
Setting param: 400
Setting param: 401
Setting param: 267
Setting param: 268
Setting param: 215
Setting param: 352
Setting param: 353
Setting param: 354
Setting param: 355
Setting param: 356
Setting param: 404
Setting param: 405
Setting param: 248
Setting param: 251
Setting param: 254
Setting param: 256
Setting param: 159
Setting param: 357
Setting param: 253
Setting param: 393
Setting param: 394
Configuration set
Checking Temperature...
Setting to Torque mode
```



```
Starting to write to file...
======================================
Average time per section:
"loop"
 * AVG :  3.521 microseconds
 * STD :  1.202 microseconds
 * MIN :      3 microseconds
 * MAX :     14 microseconds
 * %   : [3. 3. 3. 4. 4.]
```



Key lessons

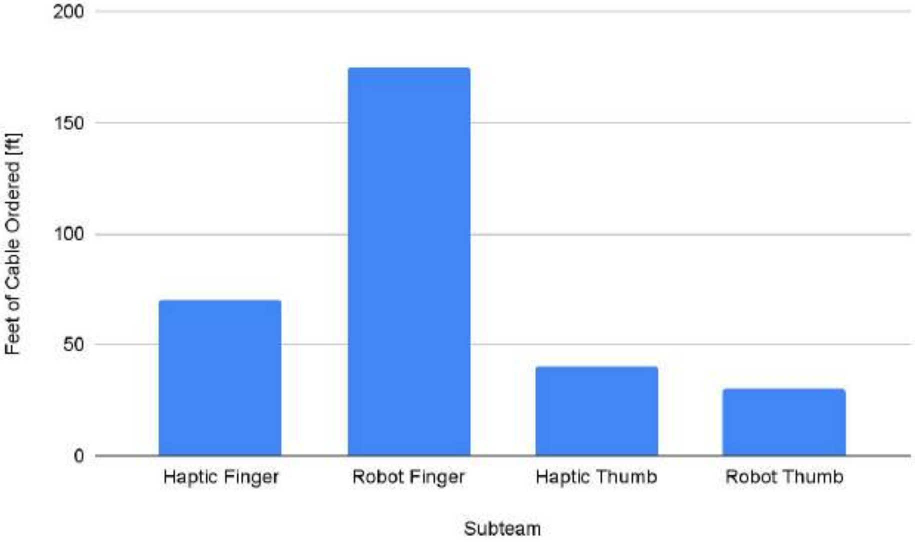
Things to keep

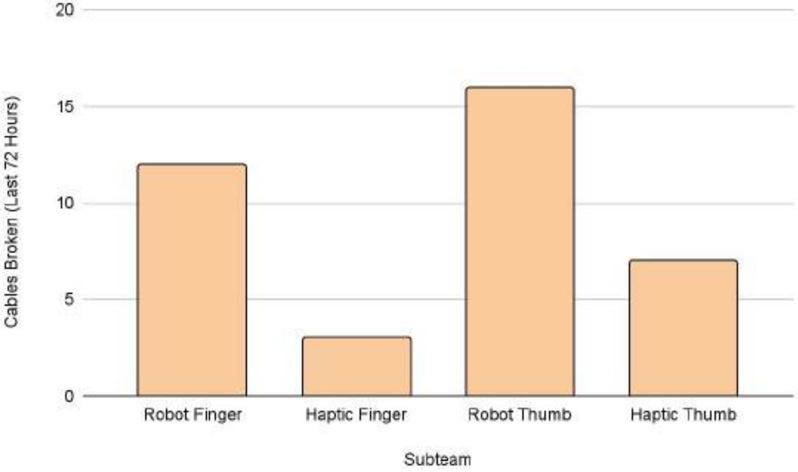
- Our magnetic encoders seem to work pretty well
- Debug LEDs very useful (A bit dimmer would be even better)
- Safety buttons / switches work well
- Overall codebase is pretty well organized
- Wires well managed

Things to change/add

- Thermistor/temperature measurement
- Relays
- Faster controller
- Not ODrive (Must control/communicate faster)
- Improved tuning
- Global safety switch
- Upgrade button perf board

Tensioning is Hard!

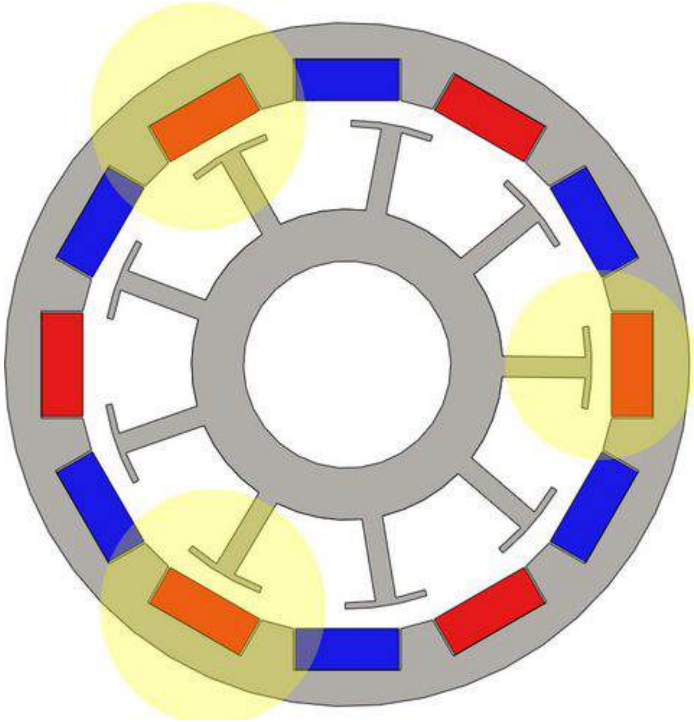




Backup Slides

Anticogging

- ODrive builds a map of cogging torque as the motor rotates during a special calibration
- Add a feedforward torque to cancel out the cogging torque, resulting in smoother operation



Control: Measuring Joint State

Let θ be the vector of joint angles

Let Φ be the vector of motor angles

The relationship between the two is given by Equation 1.

$$\vec{\theta} = \mathbb{T}\vec{\phi} + \vec{\theta_0} \quad (1)$$

The jacobian identified in Equation 1 is also used to convert velocity and torques between the motors and joints.

$$\dot{\vec{\theta}} = \mathbb{T}\dot{\vec{\phi}}$$

$$\mathbb{T}^T \vec{\tau_{joints}} = \vec{\tau_{motors}}$$

Bilateral Controller: Finger Motion

The finger bilateral control is implemented by connecting the end effector of the respective fingers by a virtual spring and damper.

$$x_r \in \mathbb{R}^2$$

$$x_h \in \mathbb{R}^2$$

$$K \in \mathbb{R}^{2\times 2}$$

$$F_r = K(x_h - x_r)$$

$$F_h = K(x_r - x_h)$$

$$\tau_r = J_r^T F_r$$

$$\tau_h = J_h^T F_h$$