LELAND ROBOTICS QUIXILVER 604

Scrappy, Not Crappy

604’s Unique Approaches to Solving Common Resource Constraints

James Best and Eugene Fang - FIRST Mentor Conference 8/25/2024

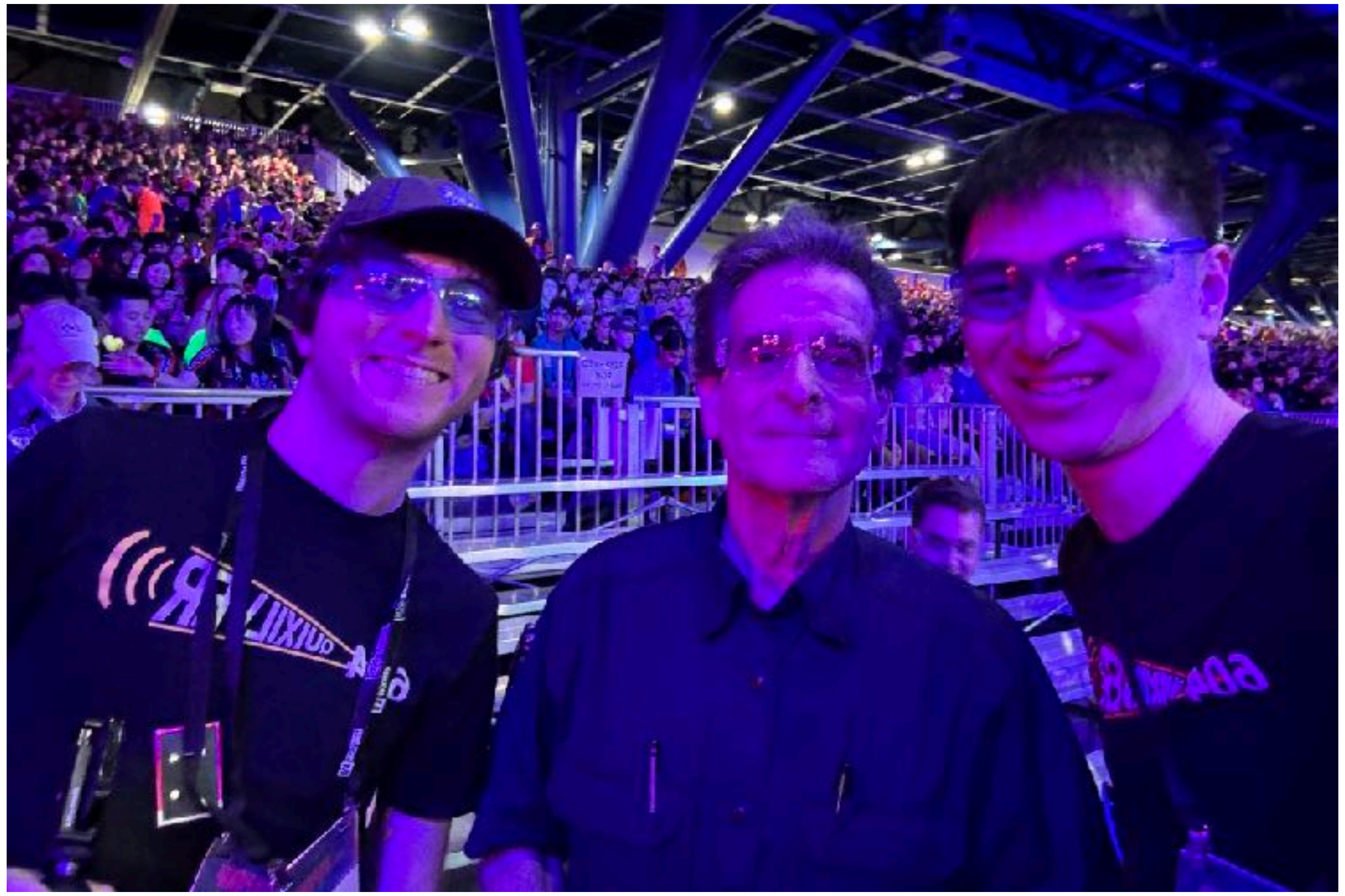
About Us

2000-2006: FLL students (same team)

2007-2010: Students on 604

2011-2020: Remote advisors for 604

2021-present: Mentors on 604



Preface

- We are sharing how we work around our specific team constraints
- Design your processes around your team's constraints
- How can you give your students the best experience within you resources?
- Don't copy what we do 1:1; use this as inspiration for your own team

Topics

- Manufacturing

  Manufacturing with jigs and 3D printing to mitigate limited machine tool access
- Modeling

  Model-based design to be efficient with time and money
- Portability

  Designing for portability to work around facility limitations
- Simulation

  Using simulation to make up for limited time with the robot

Manufacturing

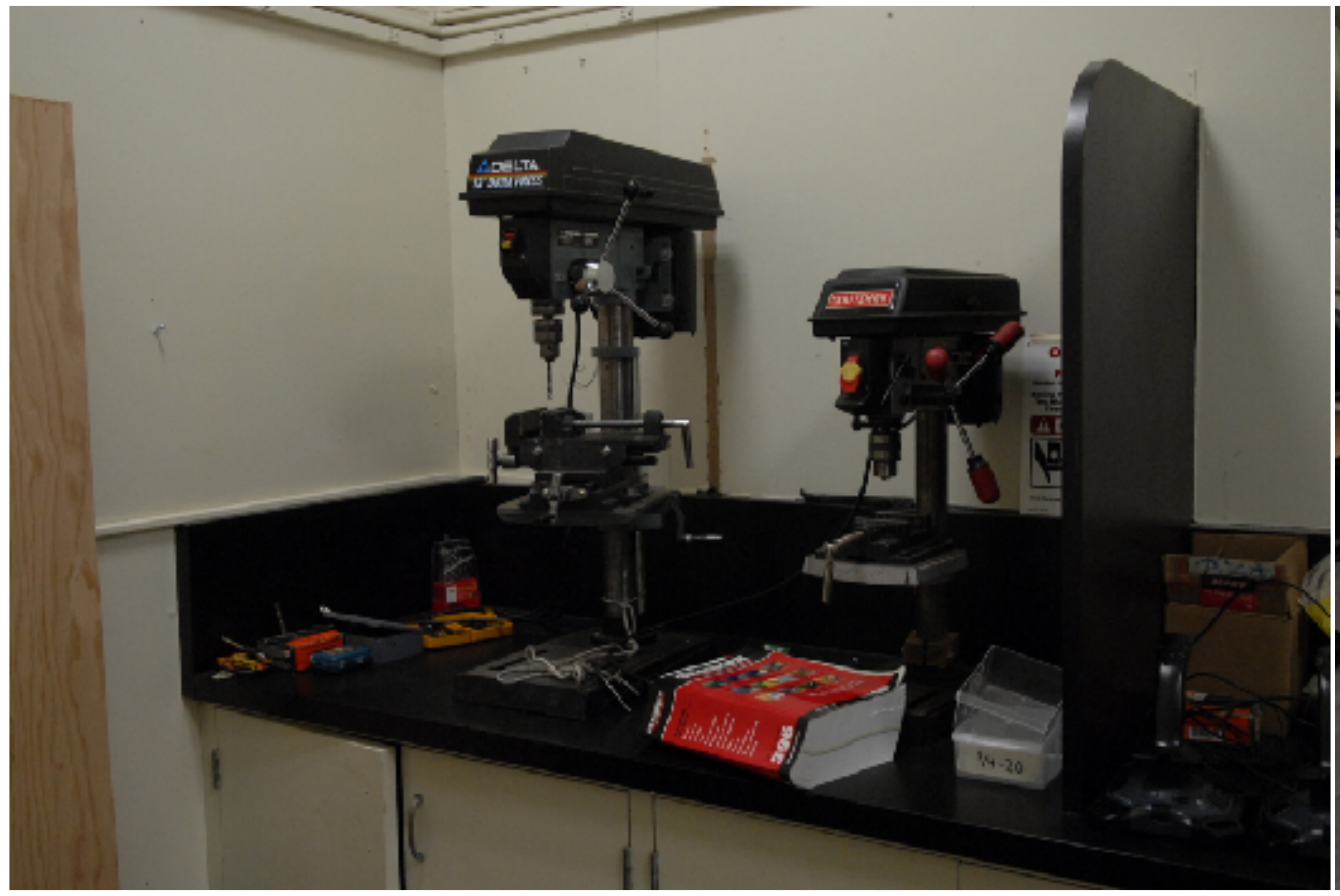
Manufacturing

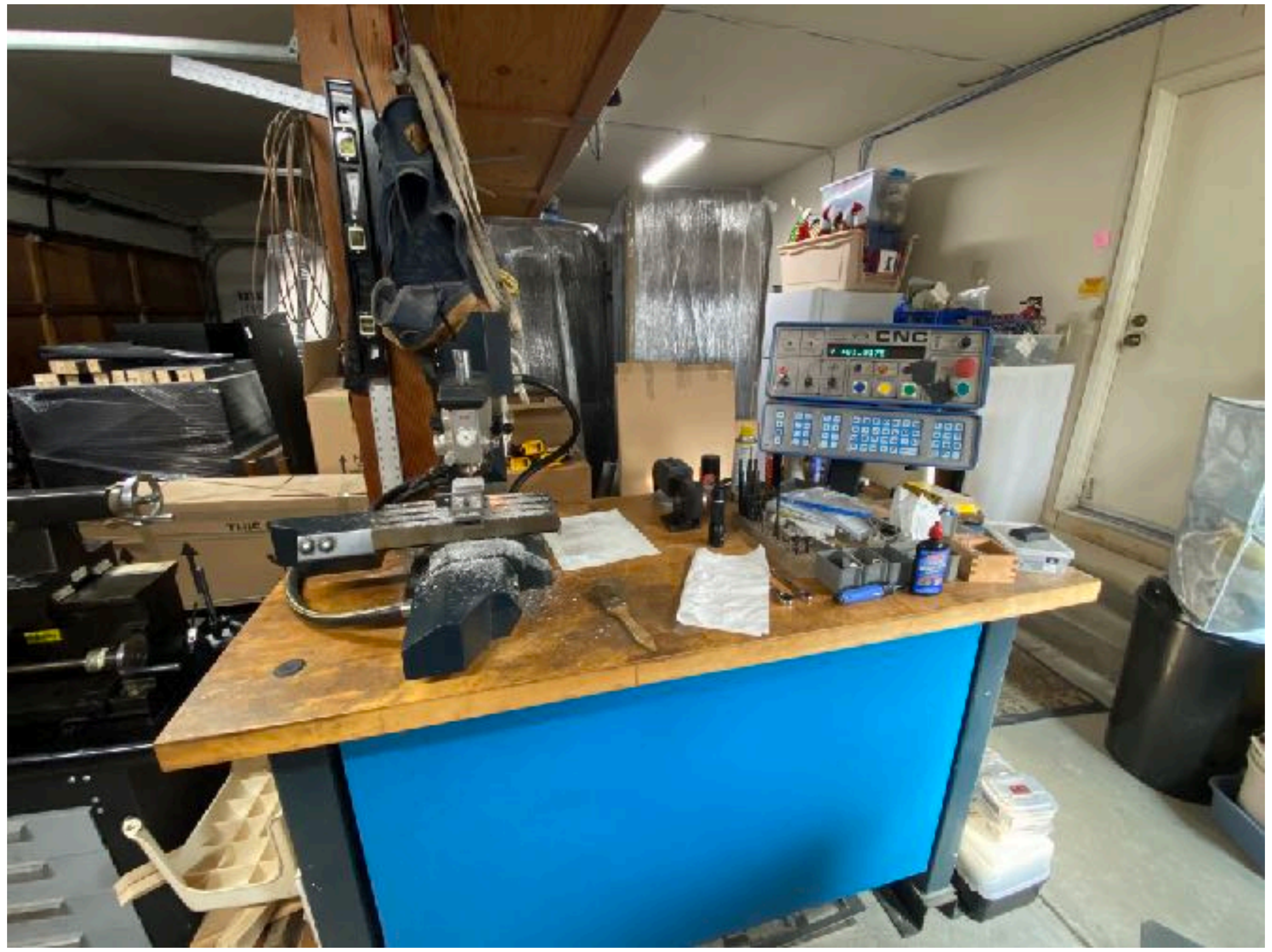
604's Manufacturing Constraints

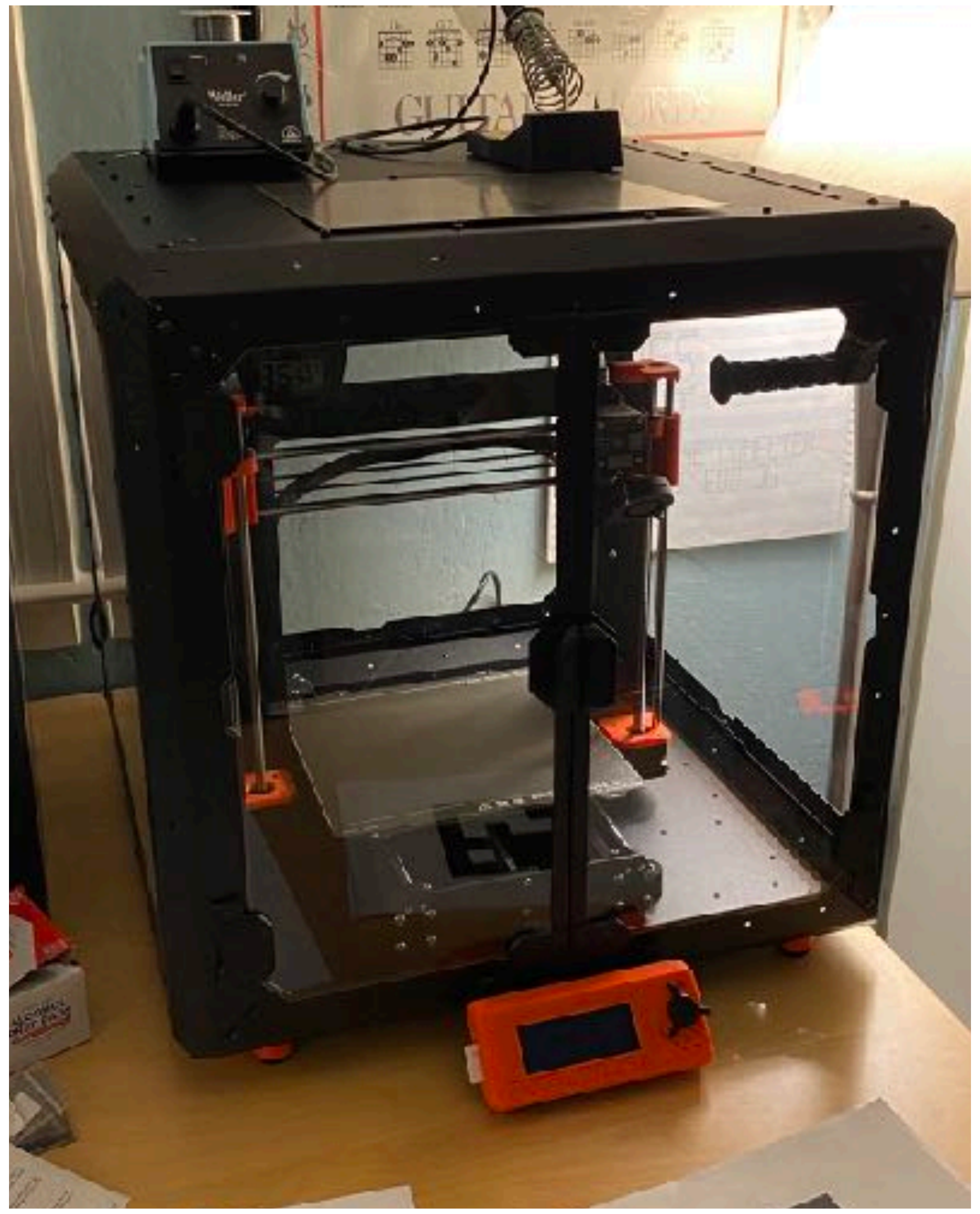
Team Tools
- Common hand tools
  - Hand drill, jigsaw, etc…
- Drill press
- Miter Saw

Student Tools
- Prusa 3D printers (~10 across the team)

Mentor Tools
- Combo mill/lathe (awful)
- Mini CNC mill (small, old, and VERY slow)
- Networking (ask other teams for a favor)







Manufacturing

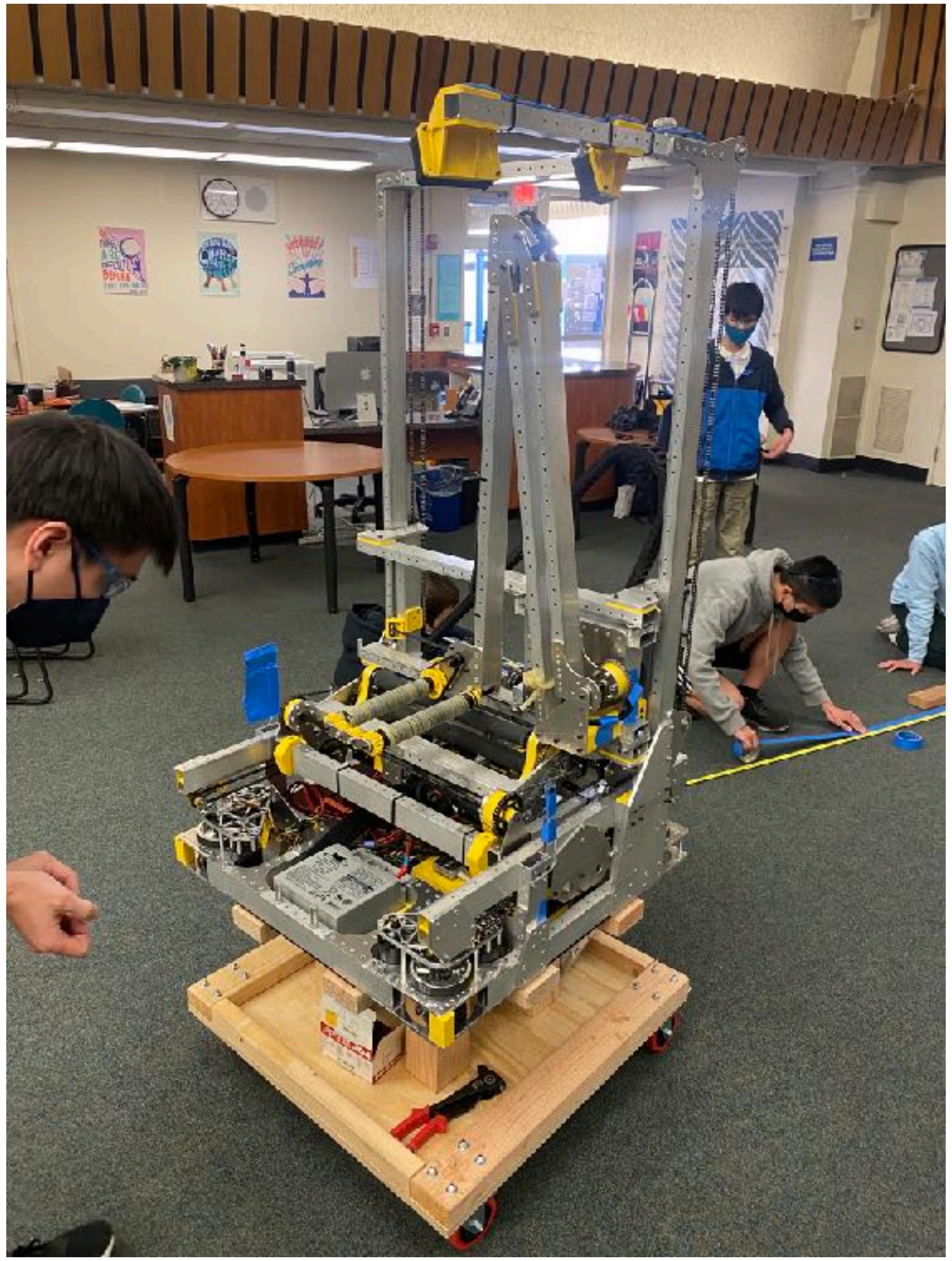
Robot Construction

How we build a robot

- Tubing
- Thin plate gusset
- COTS Parts / Hardware
- ★ 3D print anything else ★

Requirements

- Manufacture with accessible tools
  - Minimal / no "machined parts"
    - 2022 Total: 2 (chain tensioner)
    - 2023 Total: 4 (tube plugs) *foreshadowing*
    - 2024 Total: 6 (chain mount + 4 tubes)
- ★ Interchangeable parts (no match drilling) ★



Manufacturing

Tubing Drill Jigs

Process

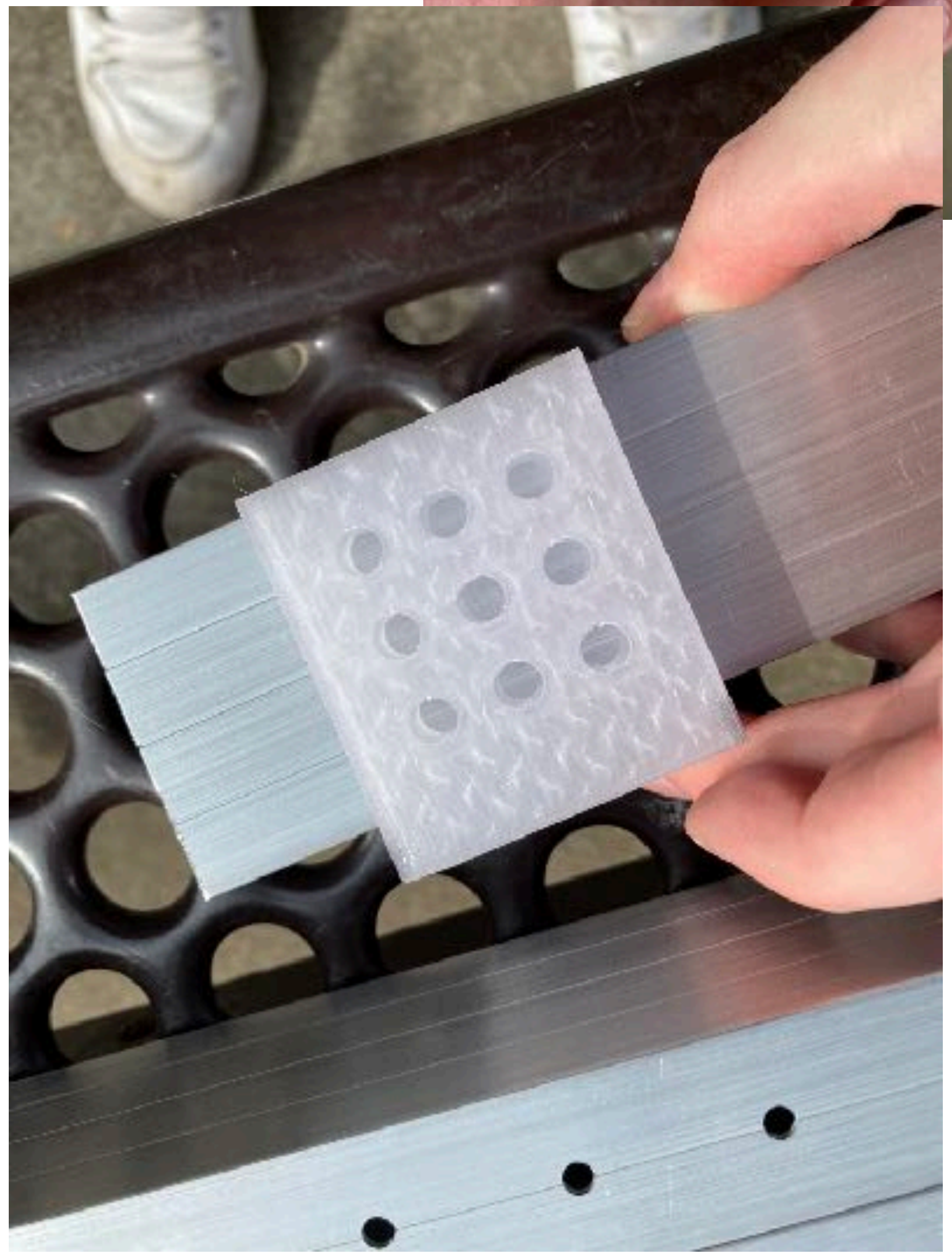
- Pins engage in punched / pre-drilled tubing
- Clamp jig to tubing
- Hand drill or drill press (preferred) desired holes

Results

- Hole position better than +/- 0.01”
  - Gussets always align
- Any student capable of making good tubing with minimal training

Why use a drill jig now that fully punched tubing is available?

- Stronger (no extra holes)
- Enables non-standard hole patterns
- Smooth surface may be needed for some mechanisms
- Aesthetics



Manufacturing

Tubing Cut Jigs

Process

- Pins engage in punched / pre-drilled tubing
- Hold in place while aligning to chop saw
- Clamp tubing to saw
- Remove jig
- Cut with miter saw

Results

- Cut accuracy is limited by rigidity of saw
  - Better with high tooth count blades
  - Edge within 0.01”-0.02” of desired

Manufacturing
Gussets

Buy (Fabworks) vs Make (Router)?
- **Quality**: ~ Both
  - Better edge surface finish - Router
  - Good accuracy - Both
- **Lead Time**: +1 Router
  - Router can have parts in a few hours
  - Buy: Order Monday night, arrives by Saturday
- **Cost**: ~ Both (+1000000x Buy if including mentor labor)
  - Stock plates for OMIO ≅ buying the parts
    - Depends on where you buy material
- **Labor Time**: +1000000x Buy
  - Buy: no CAM, no acquiring material, no tool setup, no running router, no cleanup

Key Takeaway:
<u>Order your plates/Gussets</u> (use FRC604 for a discount from Fabworks)
- Structure your build season to work around lead times
- Router only for unavoidable turnaround times



Manufacturing

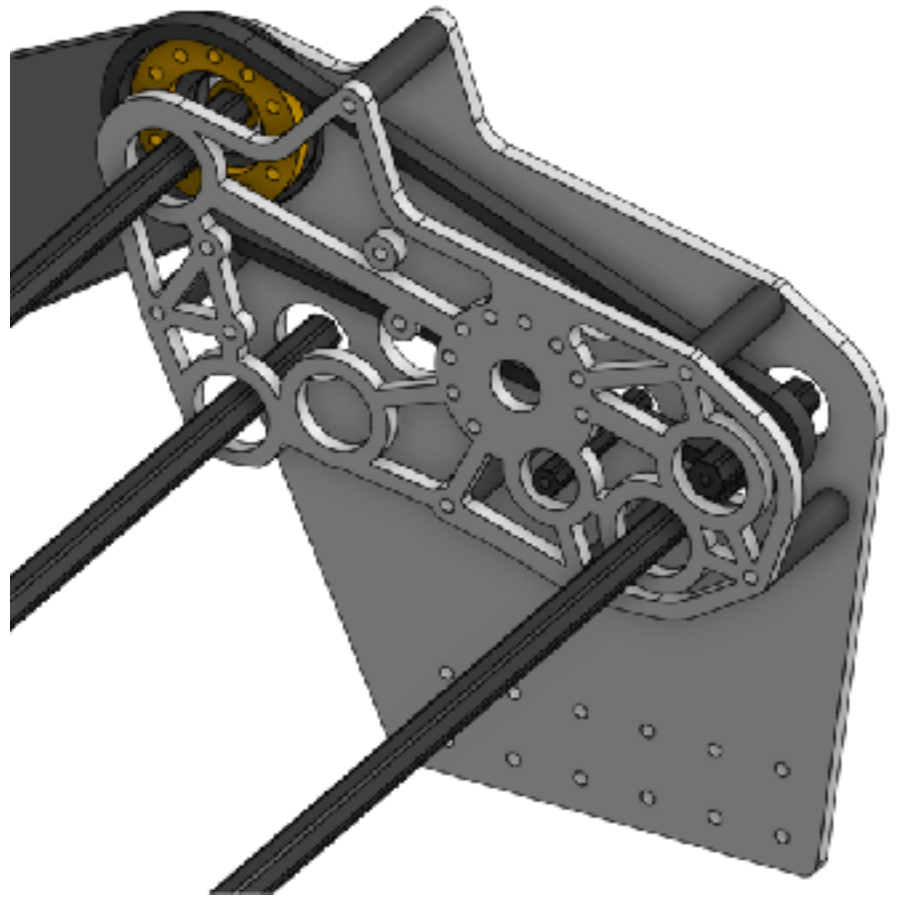
Gusset Design

Skeletonizing (commonly called pocketing)

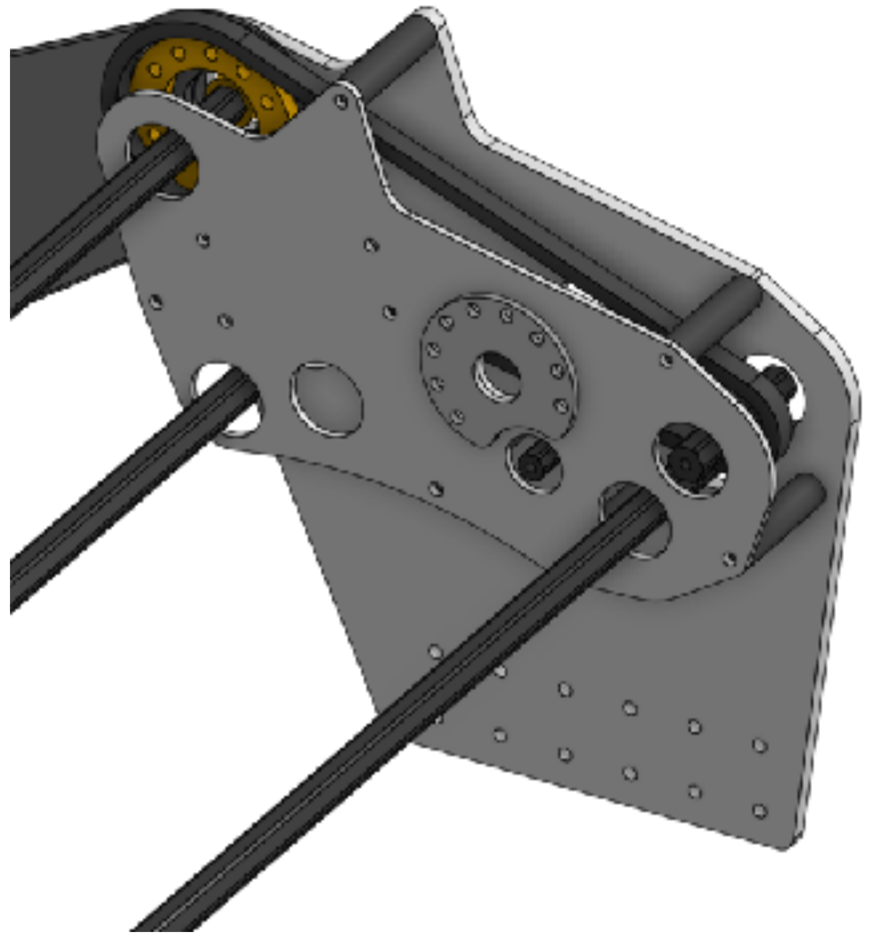
- Not the same as pocketing (leaving thin material)
  - Skeletonizing - fully cut through
- 🔥 **Hot take** 🔥: WASTE OF TIME - Don't do it
  - How do you save weight?
    - Use thinner material
    - Change your geometry

FEA (Finite Element Analysis)

- 🔥 **Hot Take** 🔥: WASTE OF TIME - Don't do it
  - How do you predict if part is strong enough?
    - Napkin math is adequately accurate
    - Load conditions are harder to estimate
- ✅ **Good** ✅ for teaching students
  - Visualize stress in material
  - Builds intuition
  - Helps teach napkin math



- 1/4" skeletonized plate
- 0.5 lbs
- + 45 minutes of CAD time (not including refinement)



- 1/8" plate w/ motor doubler plate
- 0.49 lbs
- Ready to manufacture
- <0.5x price / part

Manufacturing

Router Jigs

Process
- Use router template to mark the cut line
- Jigsaw within 1/4” of the cut line
- Clamp / adhere router template to part
- Hand router with template follower bit
  - Mentor should probably do this

Results
- Copies the template into the part
- Accuracy is limited by the template

Making Templates
- 3D print
- Order an aluminum copy of the part from Fabworks
  - Can use extra aluminum copies as temporary parts for the robot

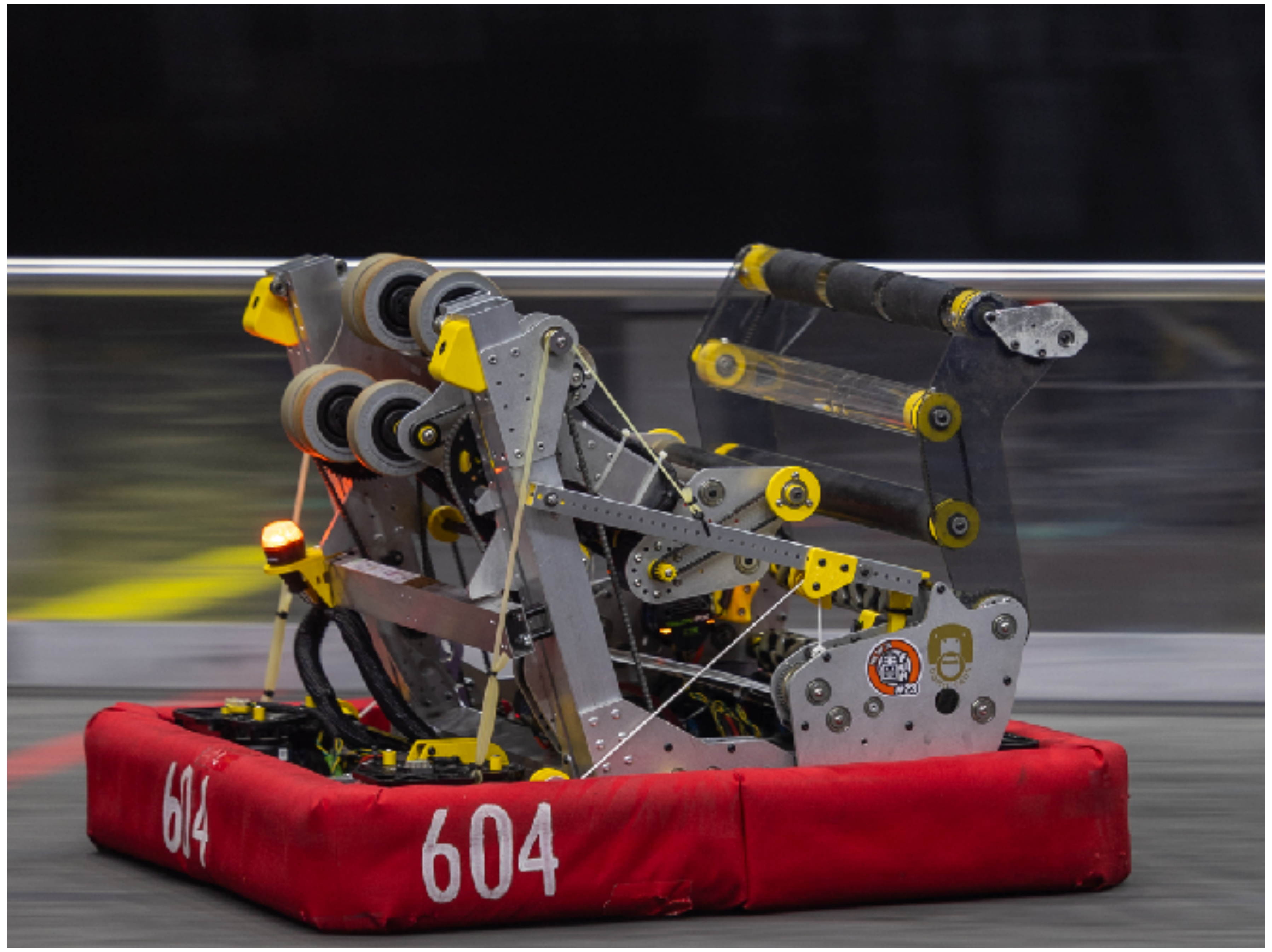
Limitations
- Only tested with wood and polycarbonate
- Don’t recommend aluminum (sketchy)

Manufacturing

3D Printing - If It's Yellow, It's 3D Printed

2022

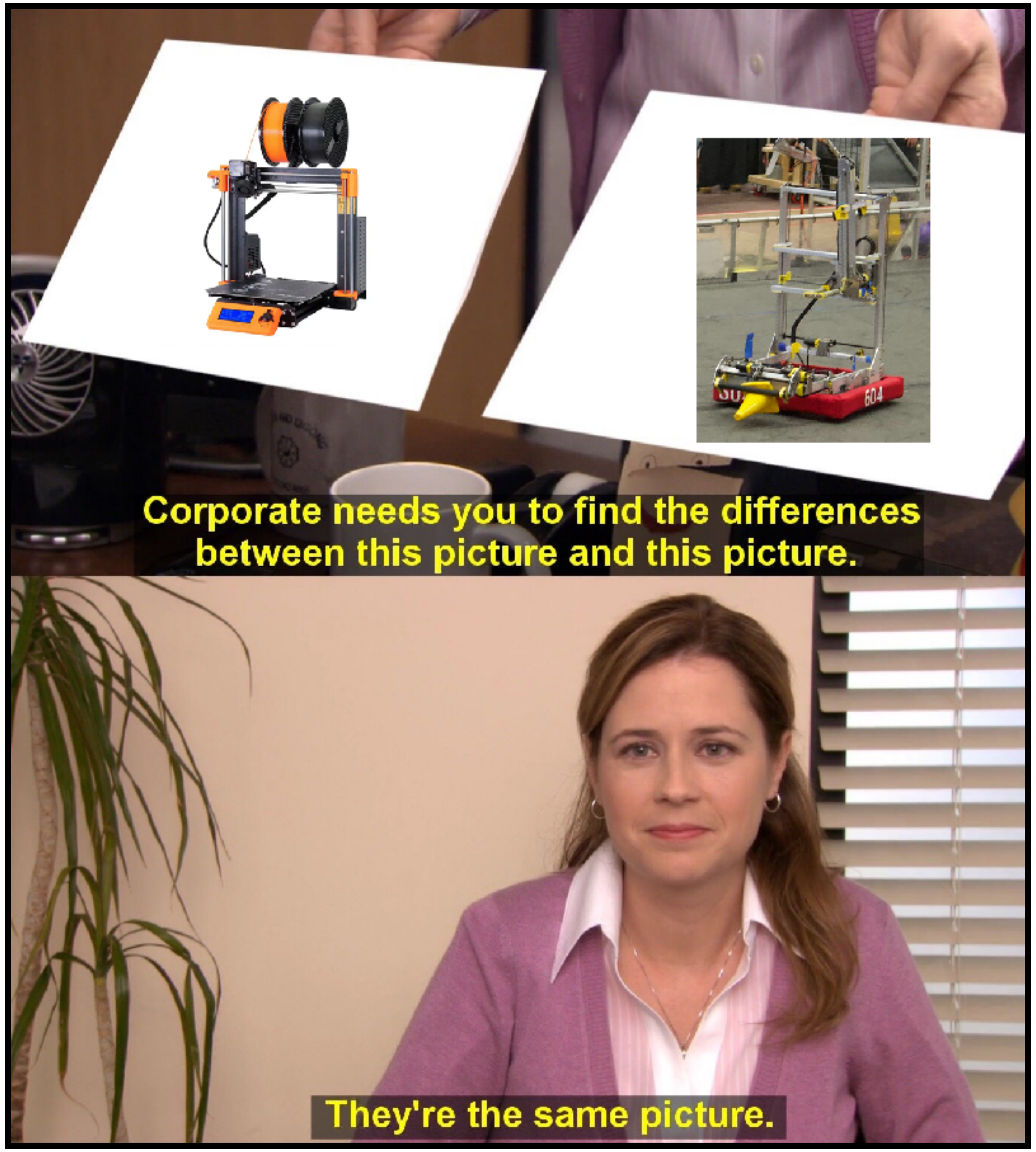
2023



2024

Manufacturing

3D Printing

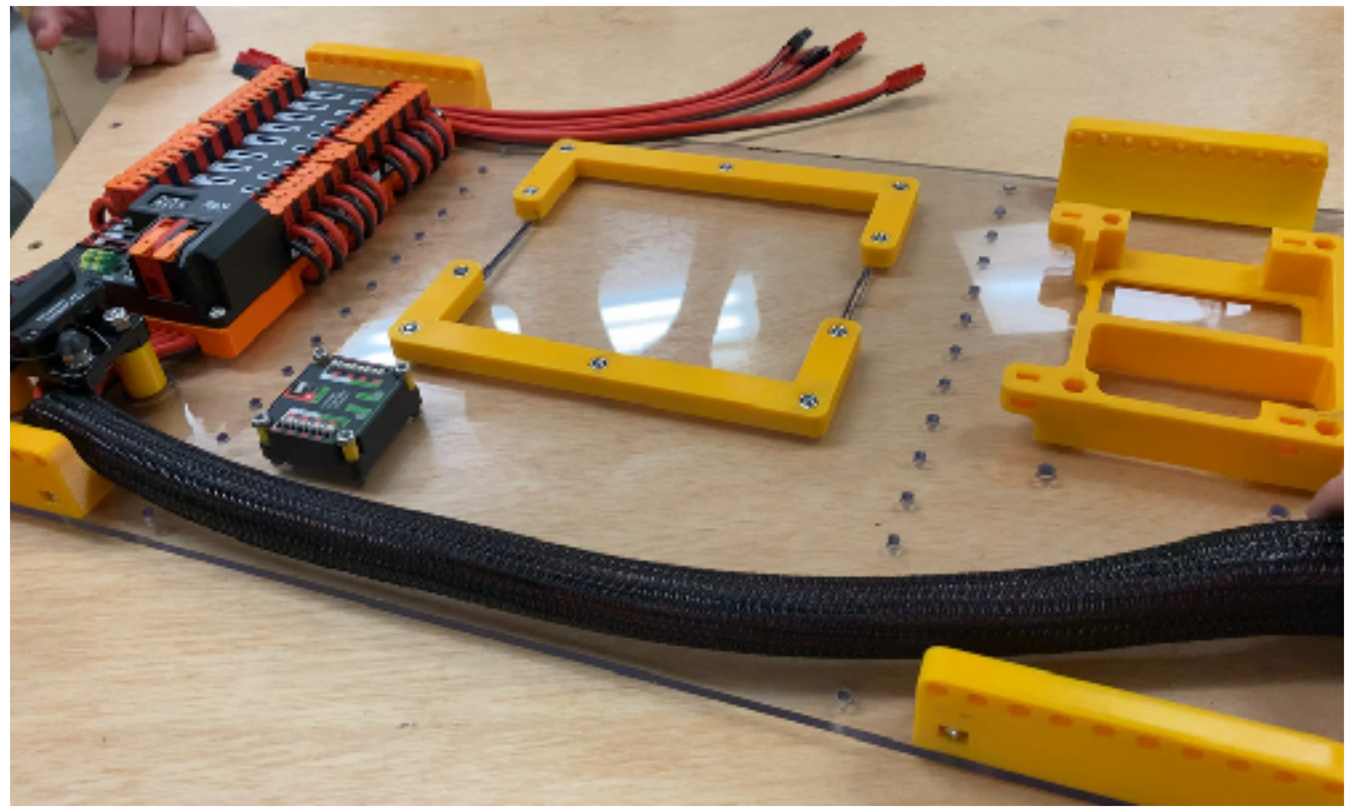


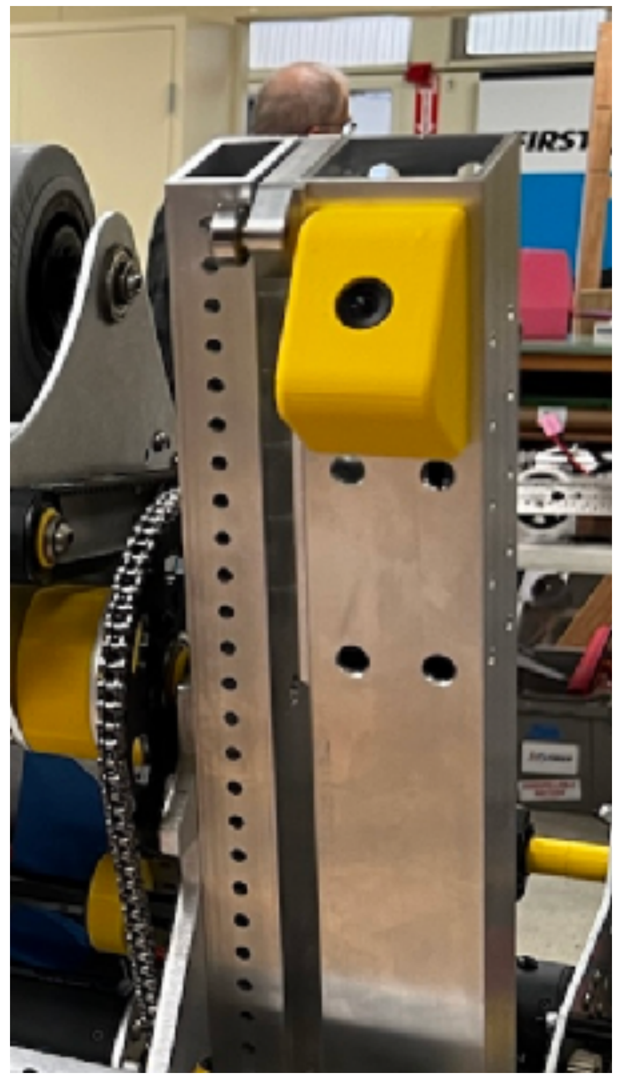
Manufacturing

Should this be 3D Printed?

Electronics Mounts?

✅ Absolutely 👍



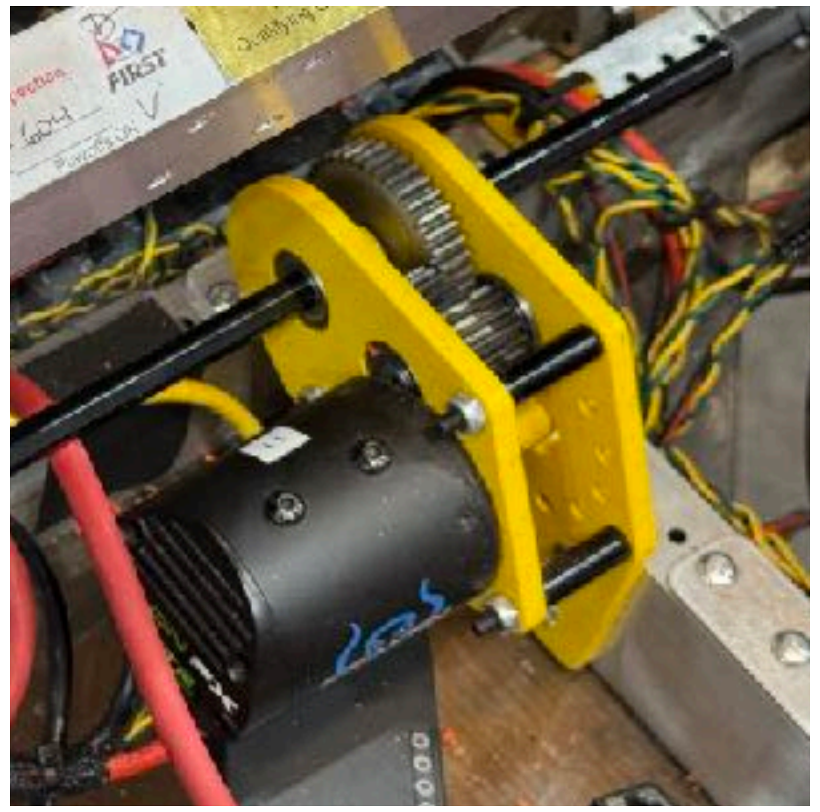


Pulleys?

✅ Good Idea 👍

Gear Boxes?

✅ Fine



Gears?

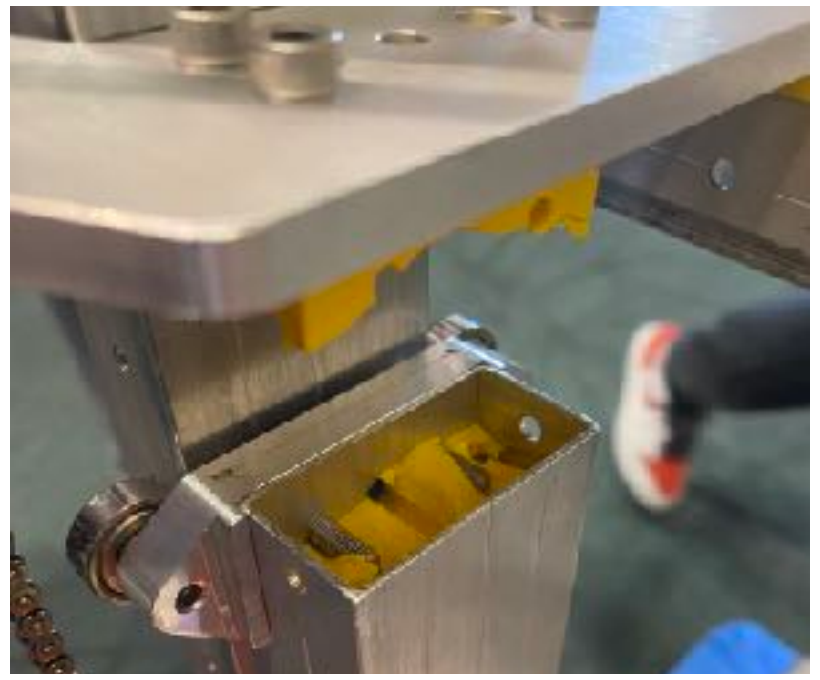
⚠️ OK with care

Sprockets?

⚠️ OK with care

Tube Plugs?

❌ Use Metal



Manufacturing

3D Printing Structural Components

Why print parts that can be made from plate?

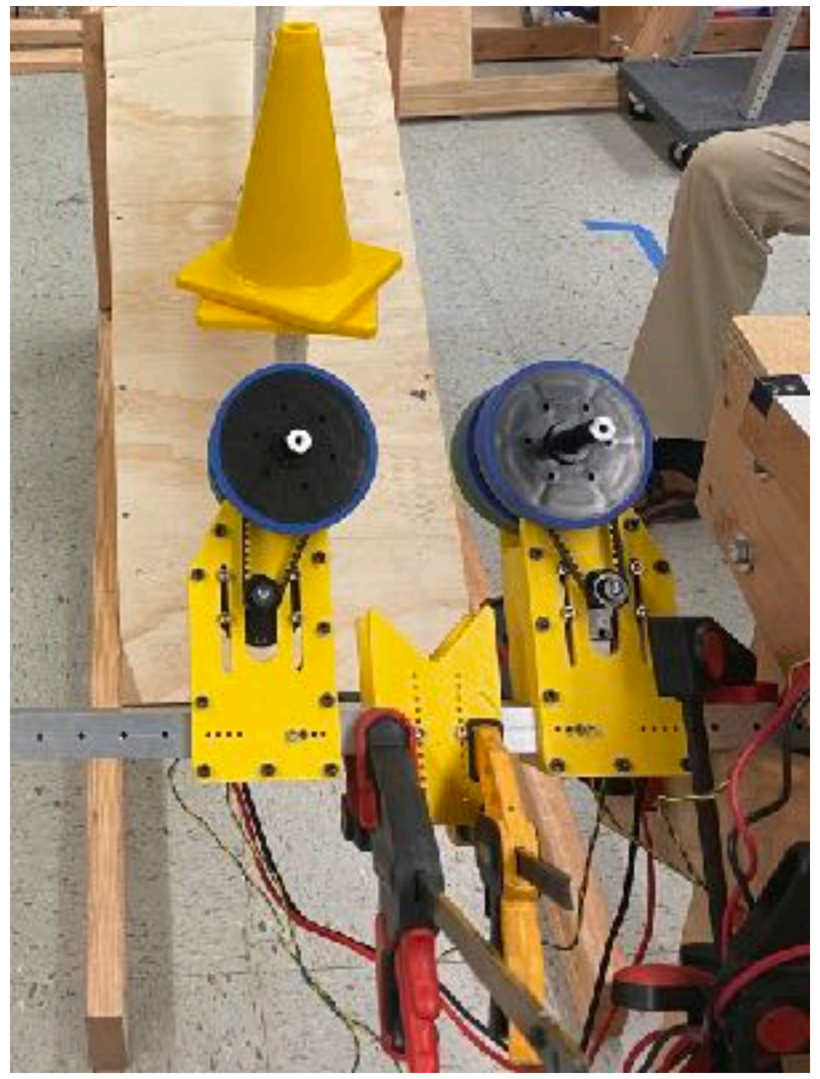
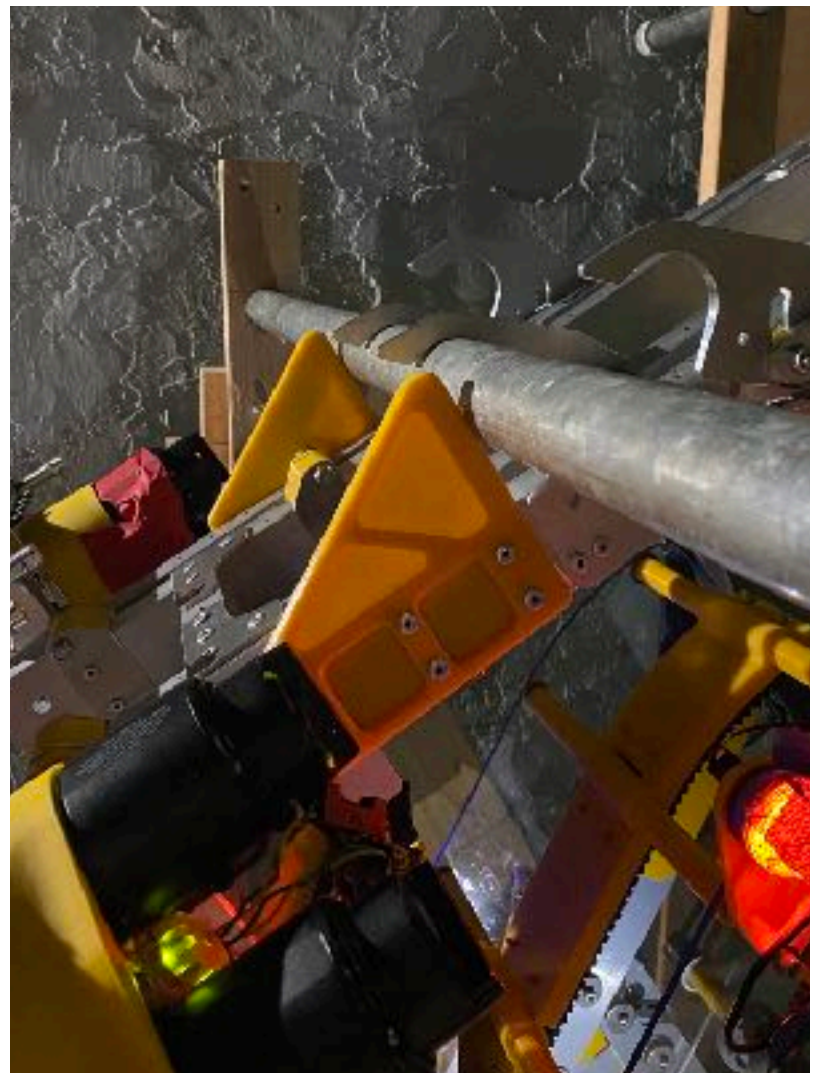
- No labor (5min), cheap, lead-time (overnight)
  - Kids print parts at home (no mentor support)
    - Same printer (Prusa) + print settings
  - Divide parts over printers to finish ASAP
  - Full mechanism ready by morning
- Parts can be upgraded during comp (print in pit)

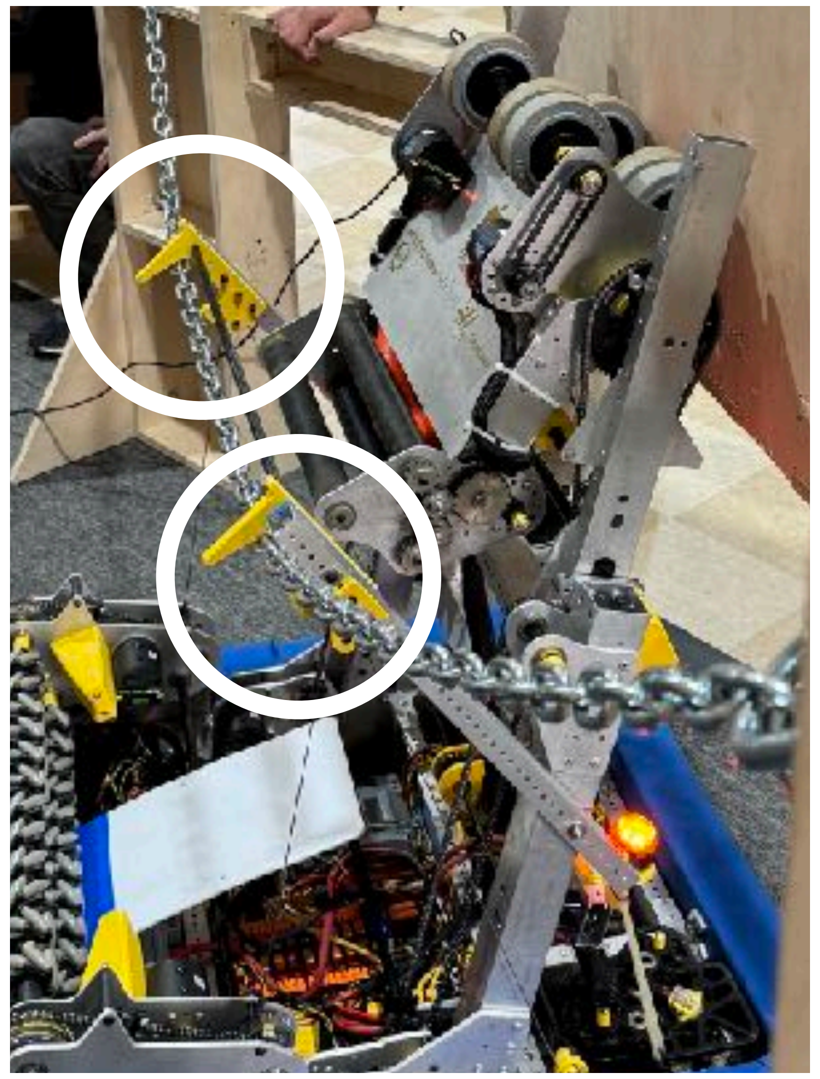
Materials and Settings

- PETG
  - Excellent layer adhesion
  - Print orientation doesn't really matter for strength
- 100% Infill only - treat the part like it's billet
  - Tap holes, lighten with pockets, etc…

Limitations

- Brittle - Impacts tend to crack parts / sudden failure




Manufacturing

3D Printing Motion Components

Only print with 100% infill

- Torque does not transmit through infill
- Design as if you were making from billet

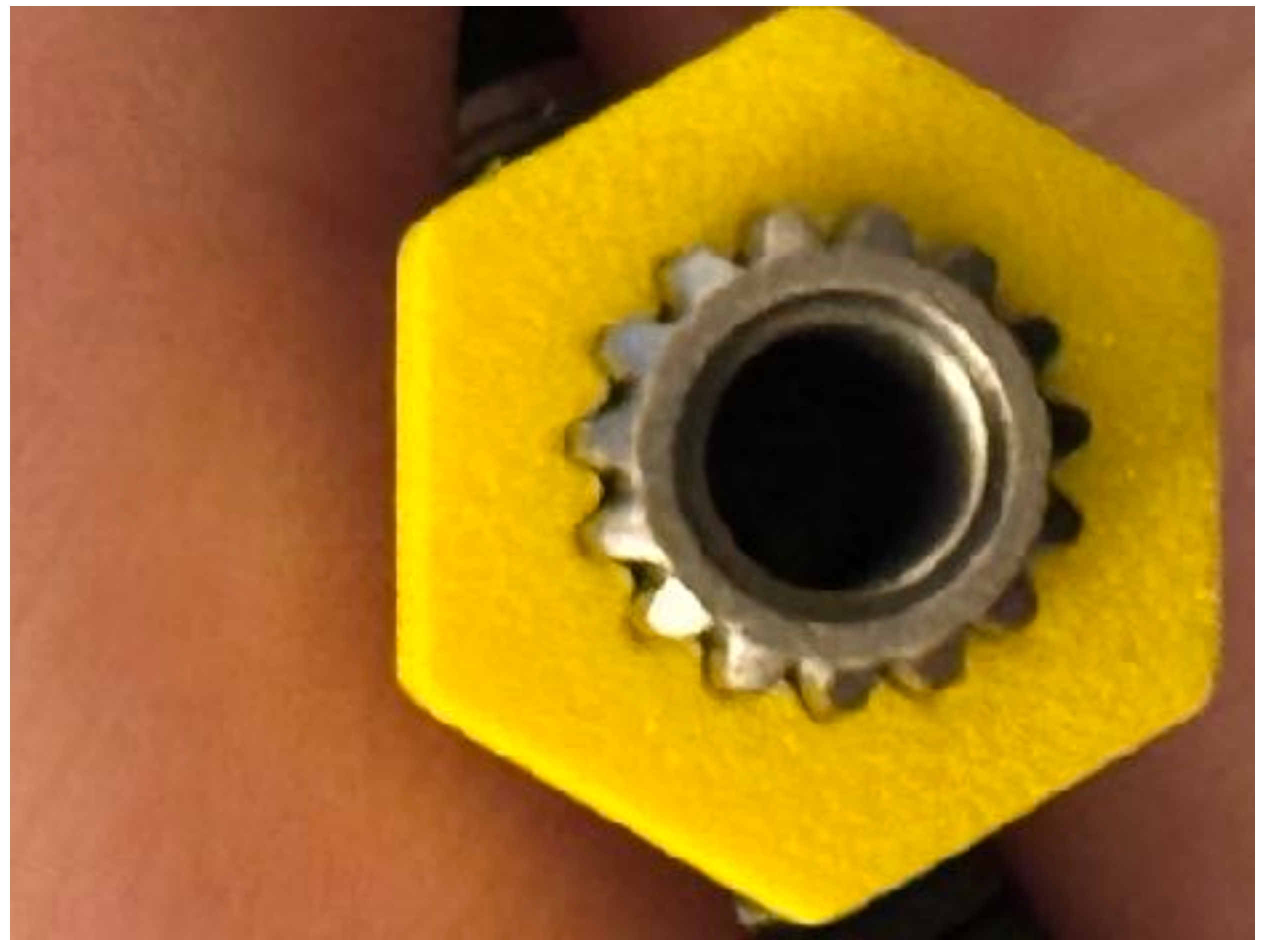
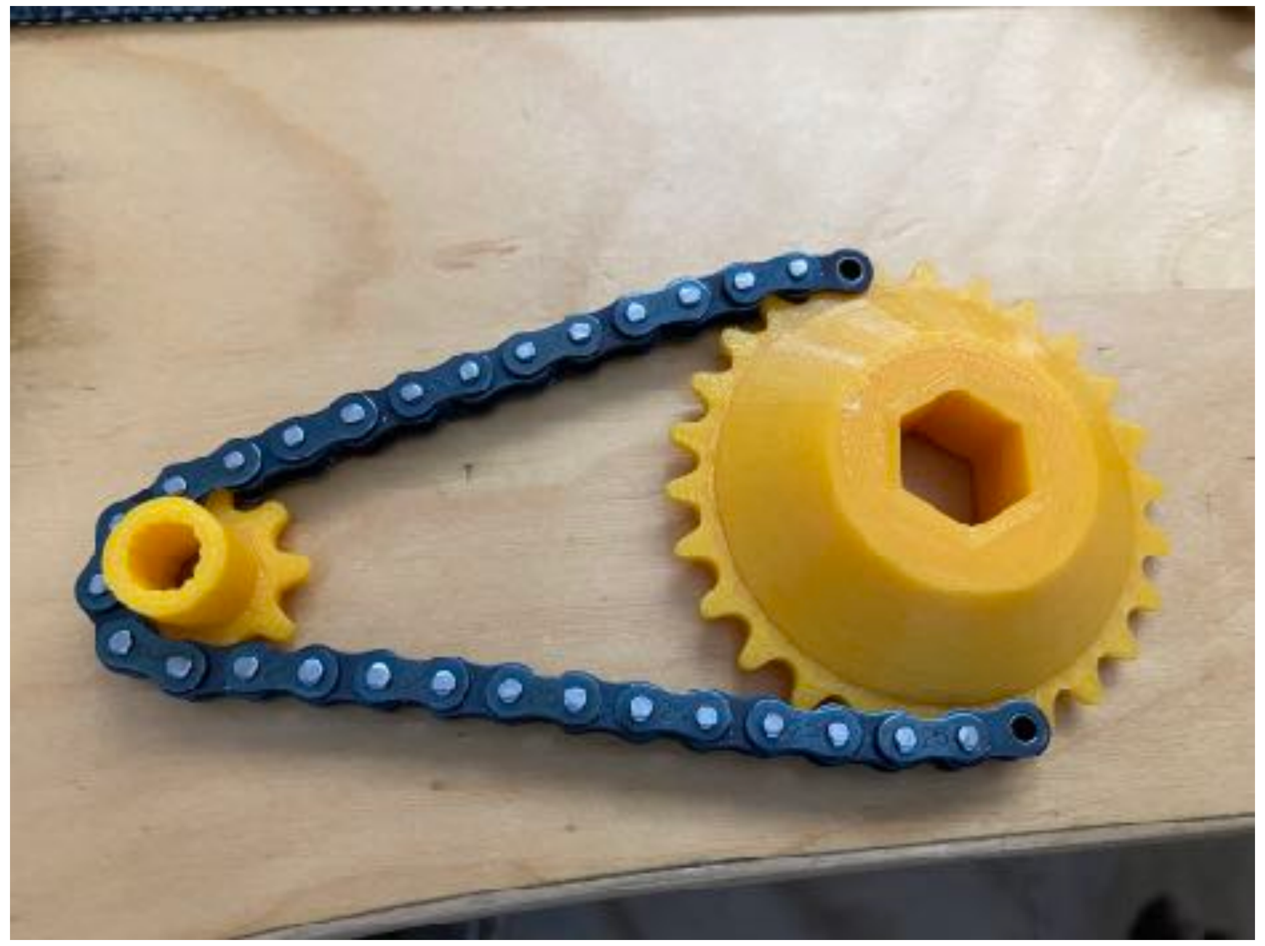
Don't directly copy metal parts

- Do some napkin math!
  - Can the spline teeth take motor torque?
  - Will the sprocket teeth fail?
  - Will the gear teeth fail?
- Do a bench test!
  - Measure strip out torque of bore
    - Use a torque wrench with shaft

Pitfalls

- Watch out for wear
- Use <u>stator</u> current limits



Modeling

Modeling

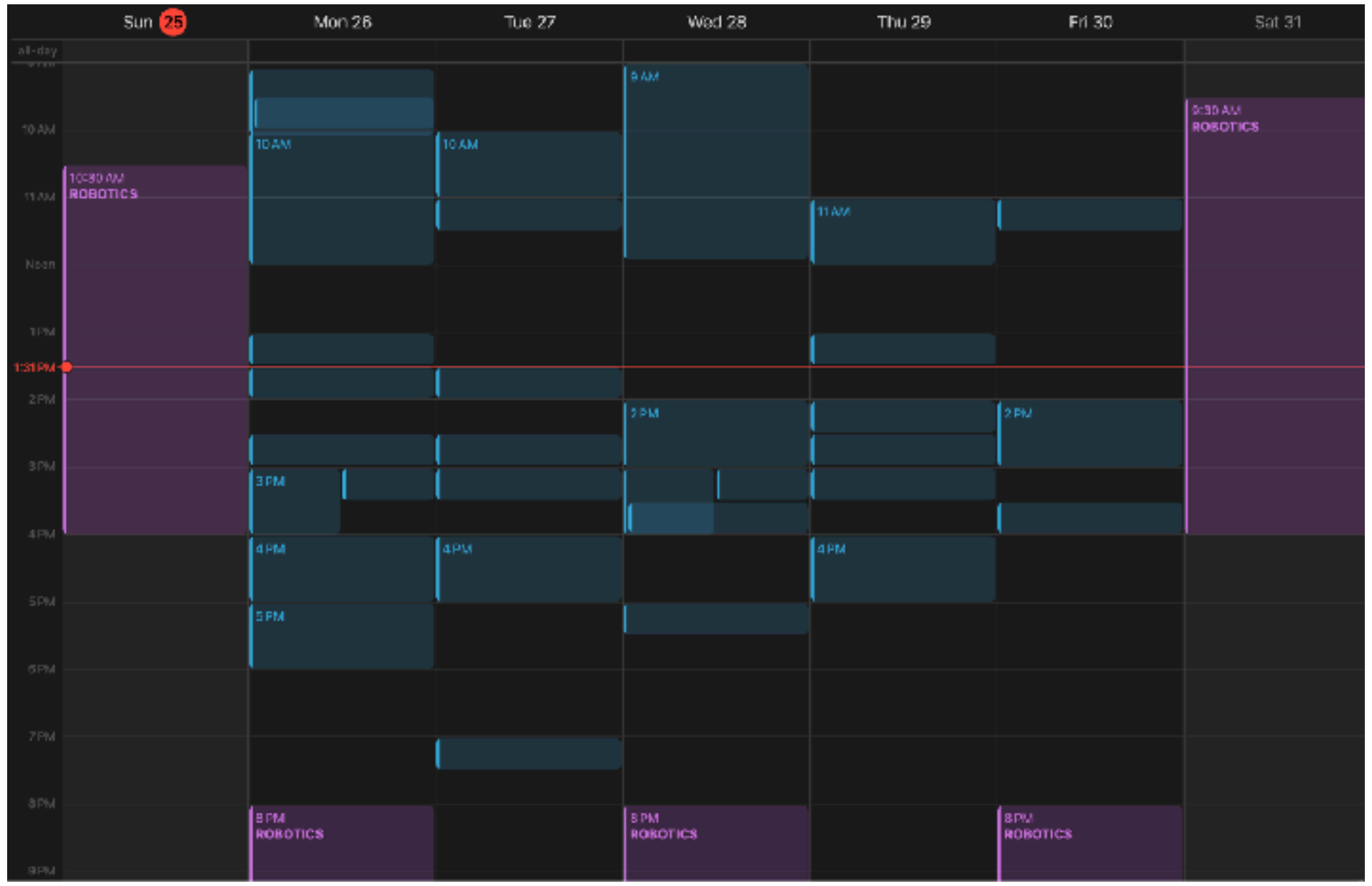
604's Meeting Constraints

Technical Mentors

- **Availability:** Weekdays - After 8pm + Weekends
- **Limitations:** Technical Mentors are not teachers
  - Can't open school room

Build Season Schedule

- Weekends in-person
  - Build & test prototypes / robot
- Weekday evenings online (~3 days a week)
  - Research (ChiefDelphi, Open Alliance)
  - Design, model, iterate
  - Option: In-person at student / mentor house
    - 2 - 3 weeks before first competition



Limitations

- Everything we build must work the first time
  - Even prototypes must have a good chance of working or at least providing very valuable data

Modeling

Why We Model

What is modeling?

- Any amount of math to predict an end result
  - Basic motor gearing math and CG calculations count as modeling!
  - Most of the stuff we do uses high-school-level math

Why Model?

- Doing some math now saves time and money later
- De-risk and solve problems as early as possible
  - Prior experience / modeling: $
  - Prototyping: $$$
  - Integration & testing: $$$$$$$$$
- In-person meeting time is precious
  - More efficient use of time & resources vs. physical iteration
  - More parallelization with limited mentor time and oversight
- Closer to real-world engineering practices

Modeling

Example: CG Estimation “Tippy G”

Why Model?

- Quickly rule out robot architectures for being too tippy
- Quickly determine weight budgets per mechanism

Model

- Spreadsheet with weighted sums to estimate CG
- Includes wheelbase to estimate ease of tipping
  - Linear acceleration “Tippy G”: >1.2 when driving
  - Turning in place: >360 deg/sec
- Calculated for every major robot configuration

Results

- Ruled out > 4 different concepts in 2023
  - Robot never tipped even when driving fully extended
- Highlighted weight budget issues early
  - Identified mechanisms for weight reduction before building

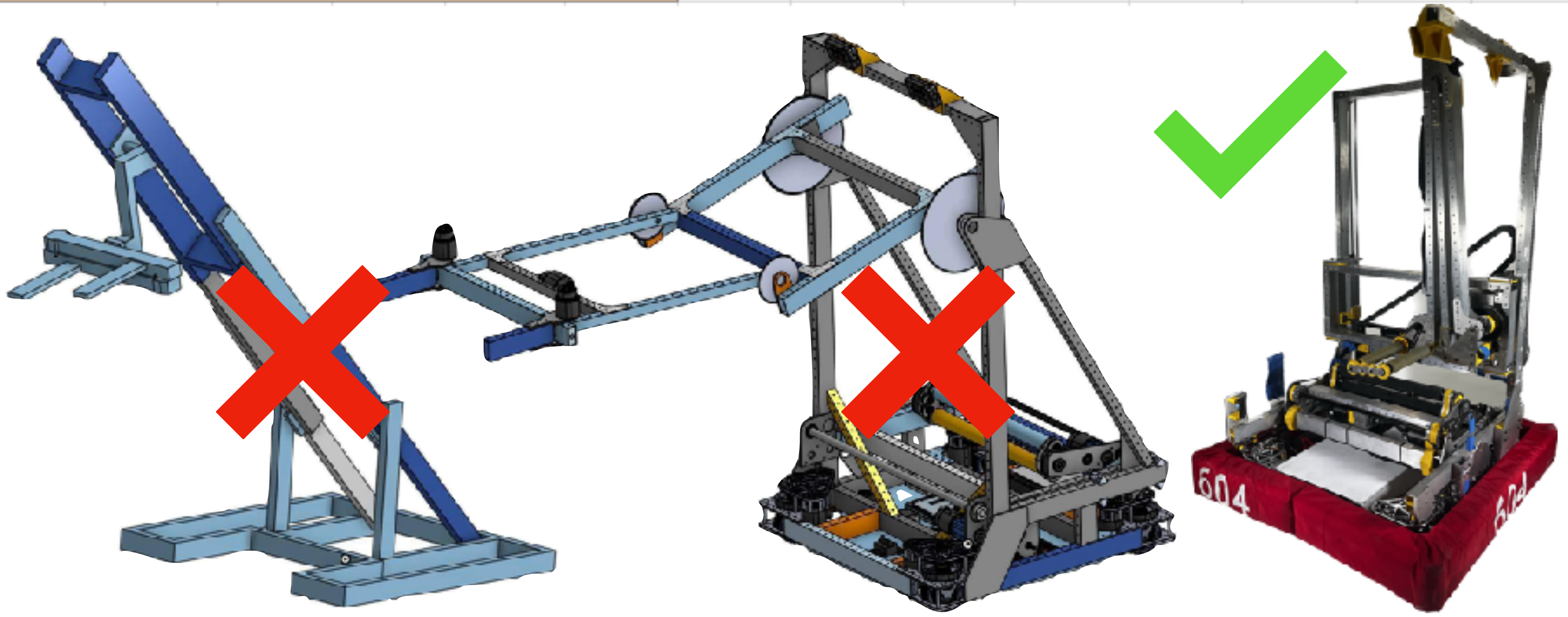
Base Components

Part	Mass	L	H	WL	WH
Frame	10	0	3	0	30
Swerve	26	0	3.5	0	91
Battery	15	10	4	150	60
Bumper	10	0	4	0	40
E Board	15	0	3	0	45
				0	0
Climber	0	0	6	0	0
Intake	20	-9	12	-180	240
				0	0
				0	0
Total	96	-0.313	5.271	-30	506
Base L	25				
Tippy G	2.312		deg/sec	#NUM!	

Include Bumpers and Battery?
TRUE

Close Speaker Arm (60deg)

Part	Mass	L	H	WL	WH
Arm	20	3	16	60	320
Arm Ele	15	5	13	75	195
Arm Su	10	5	13	50	130
				0	0
				0	0
				0	0
				0	0
				0	0
				0	0
Total	45	4.111	14.33	185	645
Total	141	1.099	8.163	155	1151
Tippy G	1.397		deg/sec	1269	



Modeling

Example: 2024 Gear Ratio Optimization

Why Model?

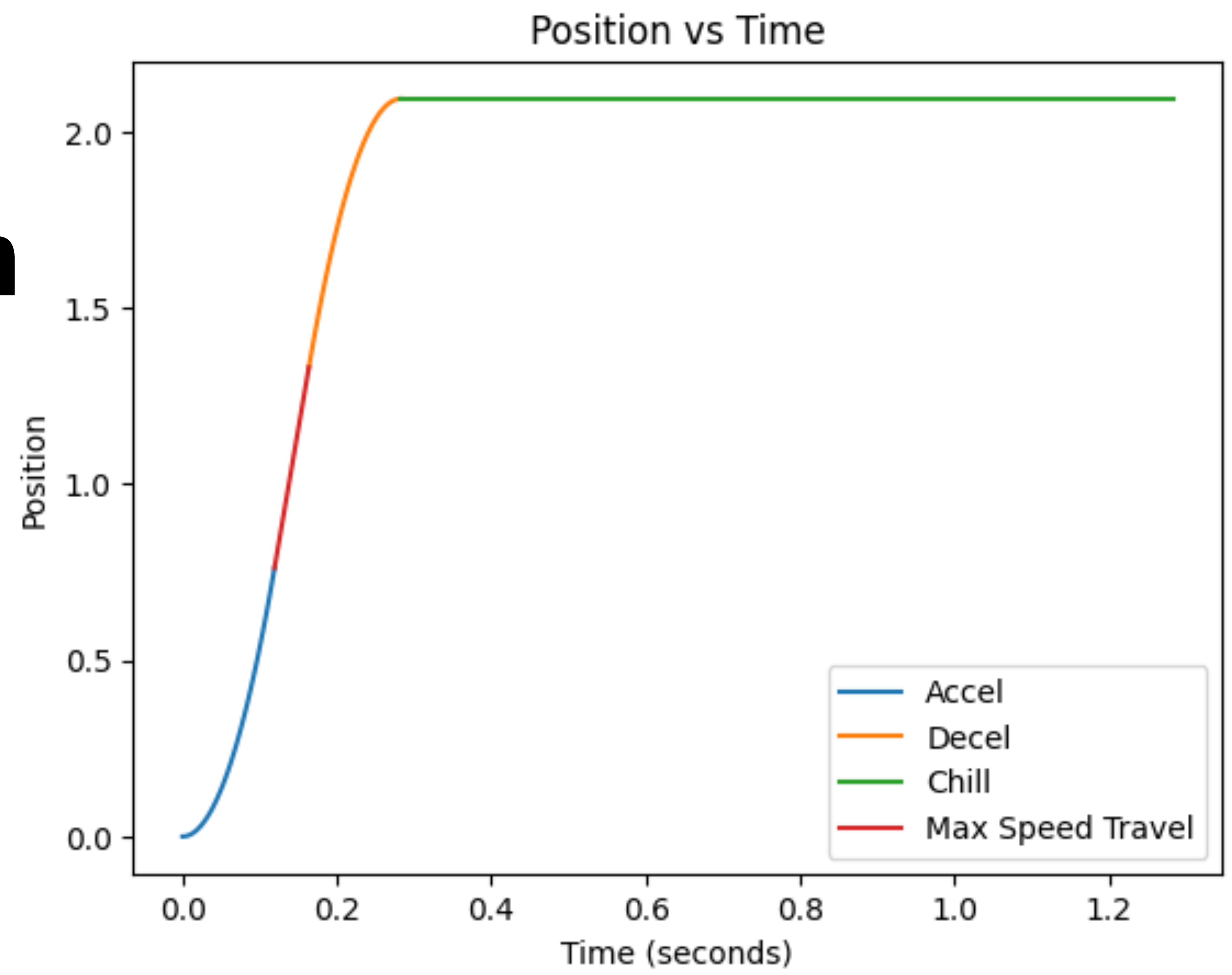
- Robot design required custom gearboxes
    - Not easily swappable gear ratio
- Maximize speed of all mechanisms
    - 2024 first year 604 optimized for speed
- Tools like ReCalc are great

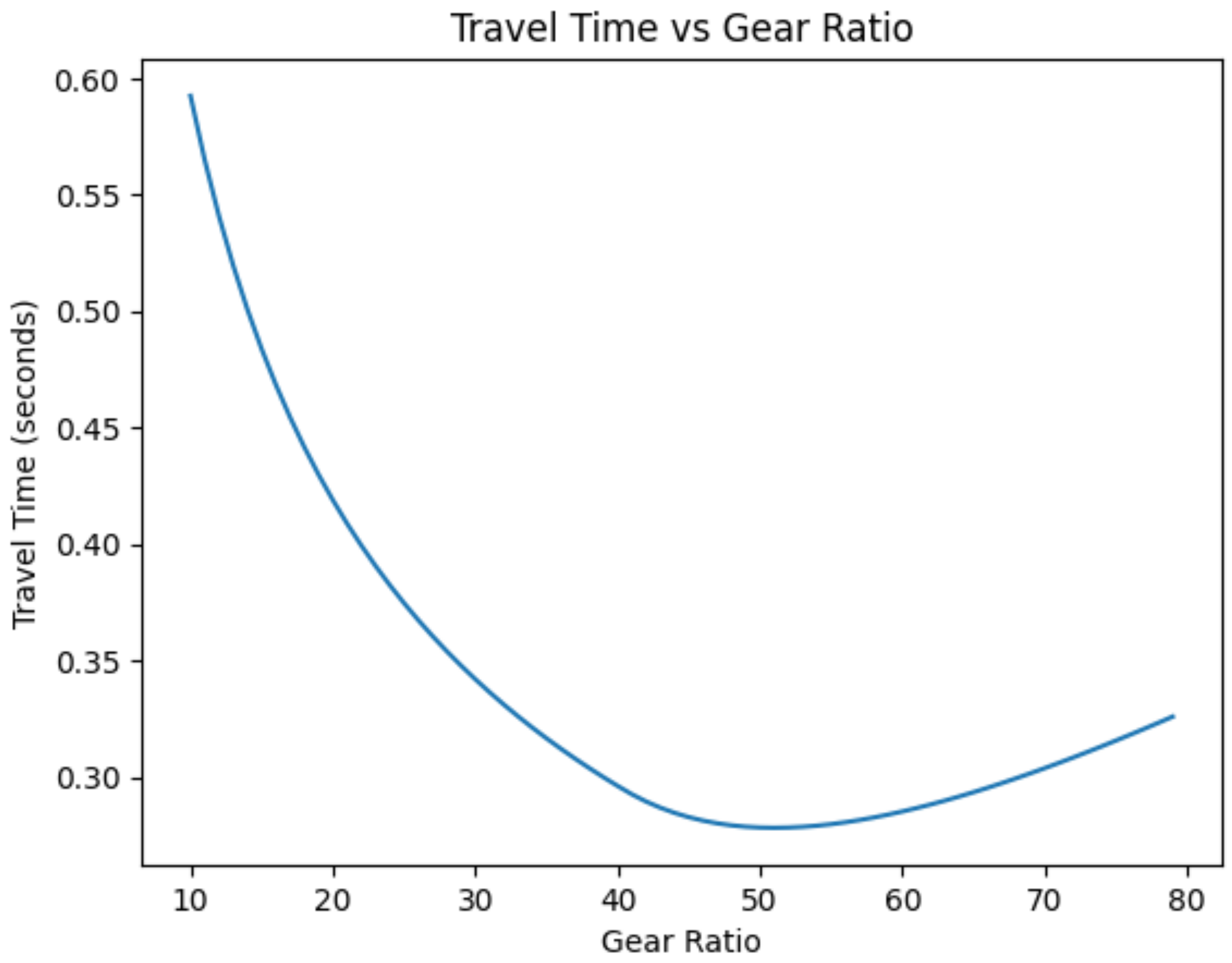
Model

- Trapezoidal motion profile
- Stator current limits torque
- Supply voltage limits speed
- Gravity offset

Results

- Motion profile limits were copied from model
    - No guess and check for tuning
- Fastest mechanisms in team's history





Modeling

Example: 2019 HAB Climb

Why Model?

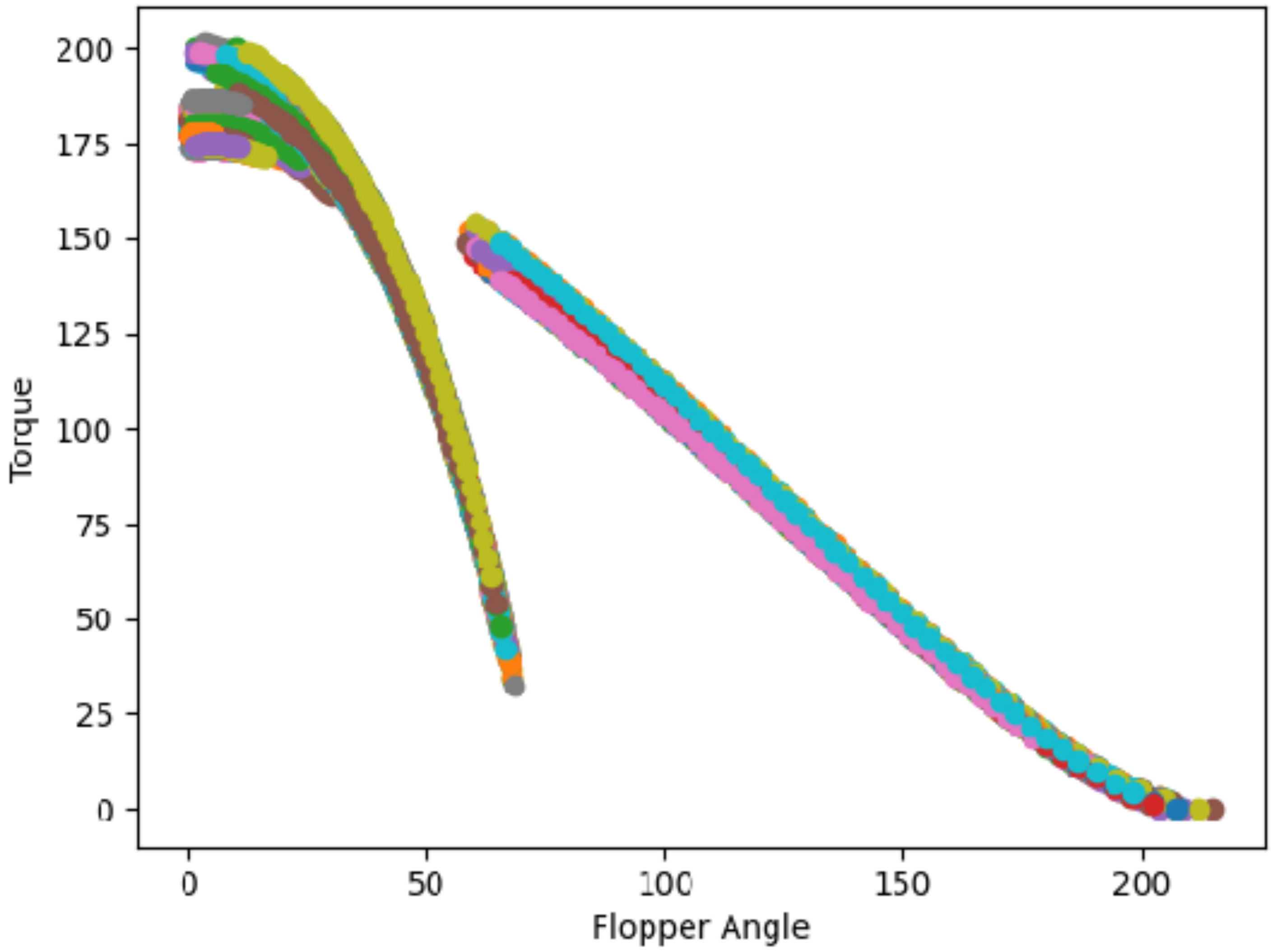
- 604 had a “unique” climb in 2019
- Concept was questionable and required the robot to be built around it
  - Needed 100% confidence it would work before committing to the concept

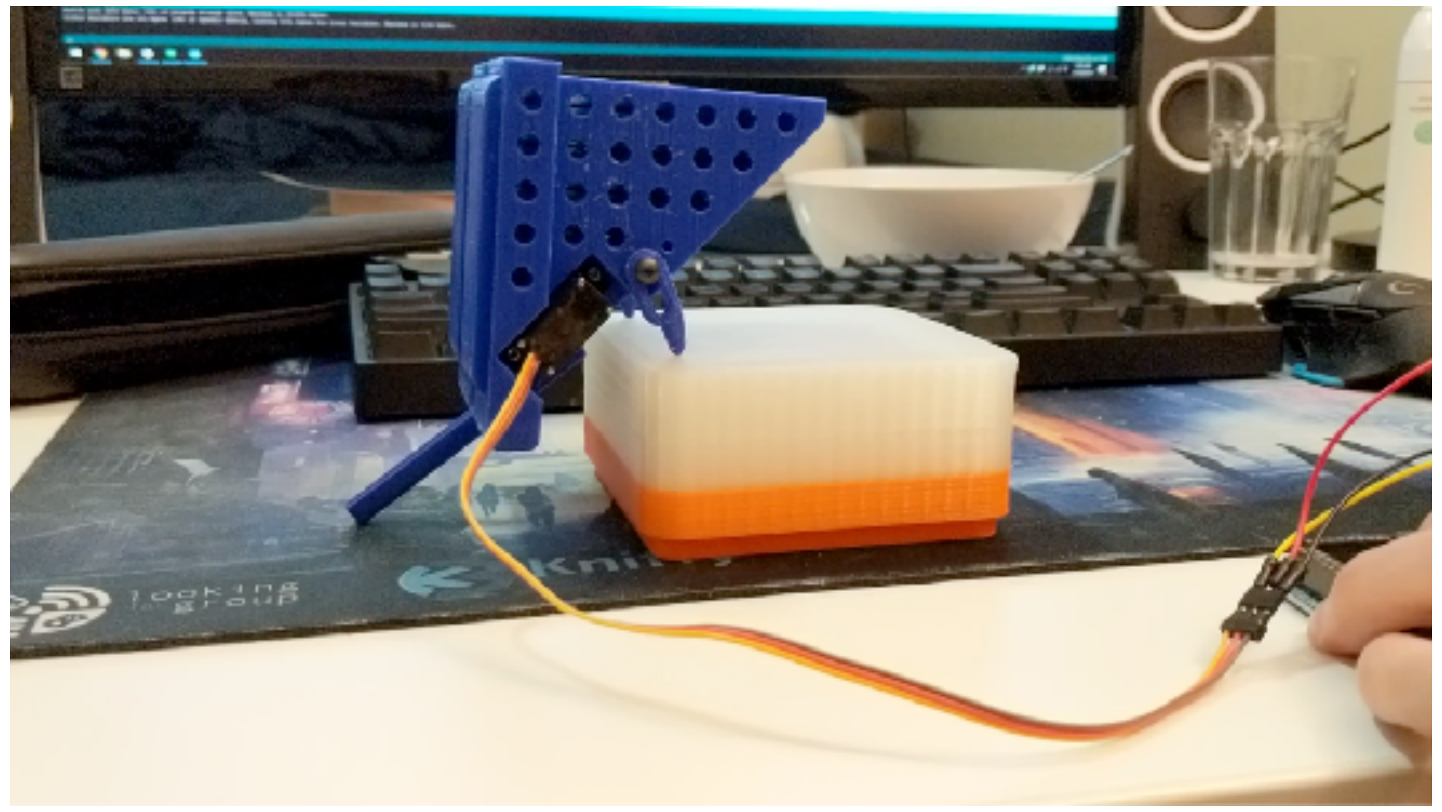
Model

- Basic geometry / trig to estimate torques
- Static analysis (easy vs dynamic)
- Included variation in manufacturing
  - Ensure CG wouldn’t become an issue

Results

- Didn’t believe it would work despite model
  - Small prototype to prove model
- Robot worked first try + every future attempt





Modeling

When to Prototype

Prototype what you can't model

- Don't skip a design because it can't be easily modeled
  - 604 2022 non-dynamic climb
  - Wasted tons of time in 2024 avoiding swinging the chain
- Avoid getting stuck modeling when it's faster to "just build it"
- Game piece interactions, especially if deformable
- 🔥 **Hot take** 🔥: Prototyping arms/elevators is a waste of time
  - ✅Learning to build an elevator != ❌Can elevator elevate

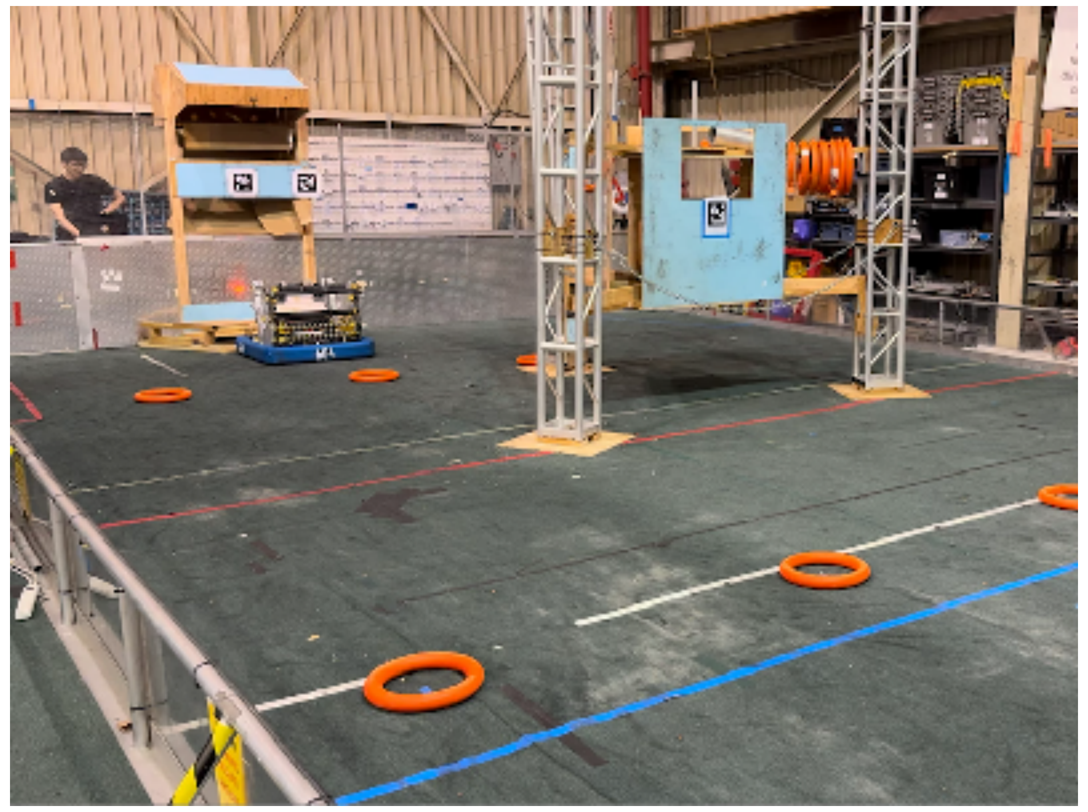
In-Person Meetings

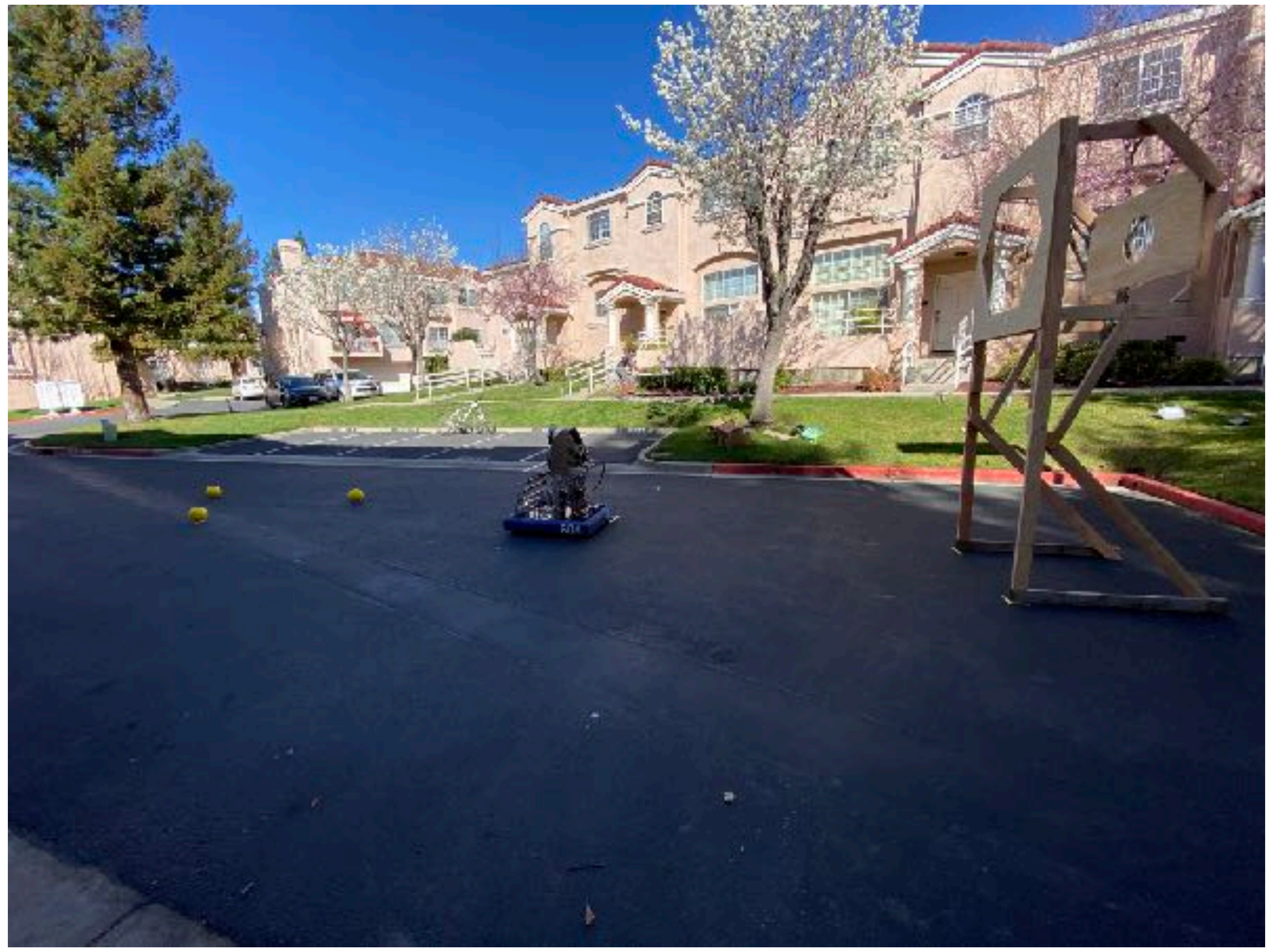
- In-Person time is valuable - use it for what you need
  - CAD / Modeling can be done online
- 🔥 **Hot take** 🔥: Most FRC teams meet in-person too much
  - Be selective with prototypes — learn from Open Alliance teams
  - If the design isn't done (prototype or robot), there's little value in meeting in-person

Portability

Portability

604's Practice Spaces





School "Library"

- **Availability:** Weekends (Saturday school takes priority)
- **Space:** Enough room for full FRC field
- **Limitations:** Must be returned to normal during school week, can't destroy carpet

Friends

- **Availability:** When our schedules align
- **Space:** Proper practice field w/elements
- **Limitations:** Need to transport stuff to and from location

Townhouse Parking Lot

- **Availability:** Until we get kicked out
- **Space:** Enough room for full FRC field
- **Limitations:** cars, neighbors, no carpet

Portability

Playing Field Elements

School "Library" Limitations
- Must convert back to normal during week
- Field elements must go back to Robotics room
  - Kids need to lift them…

FIRST Field Element Designs
- Intended to hold up to competition
  - large and heavy (hard to move)
  - expensive
  - time consuming to make

Design Your Own Field Elements
- Practice Requirements != Competition Requirements
  - What are we trying to practice with the robot?
  - What features do we need for practice?
- De-feature / simplify the field elements

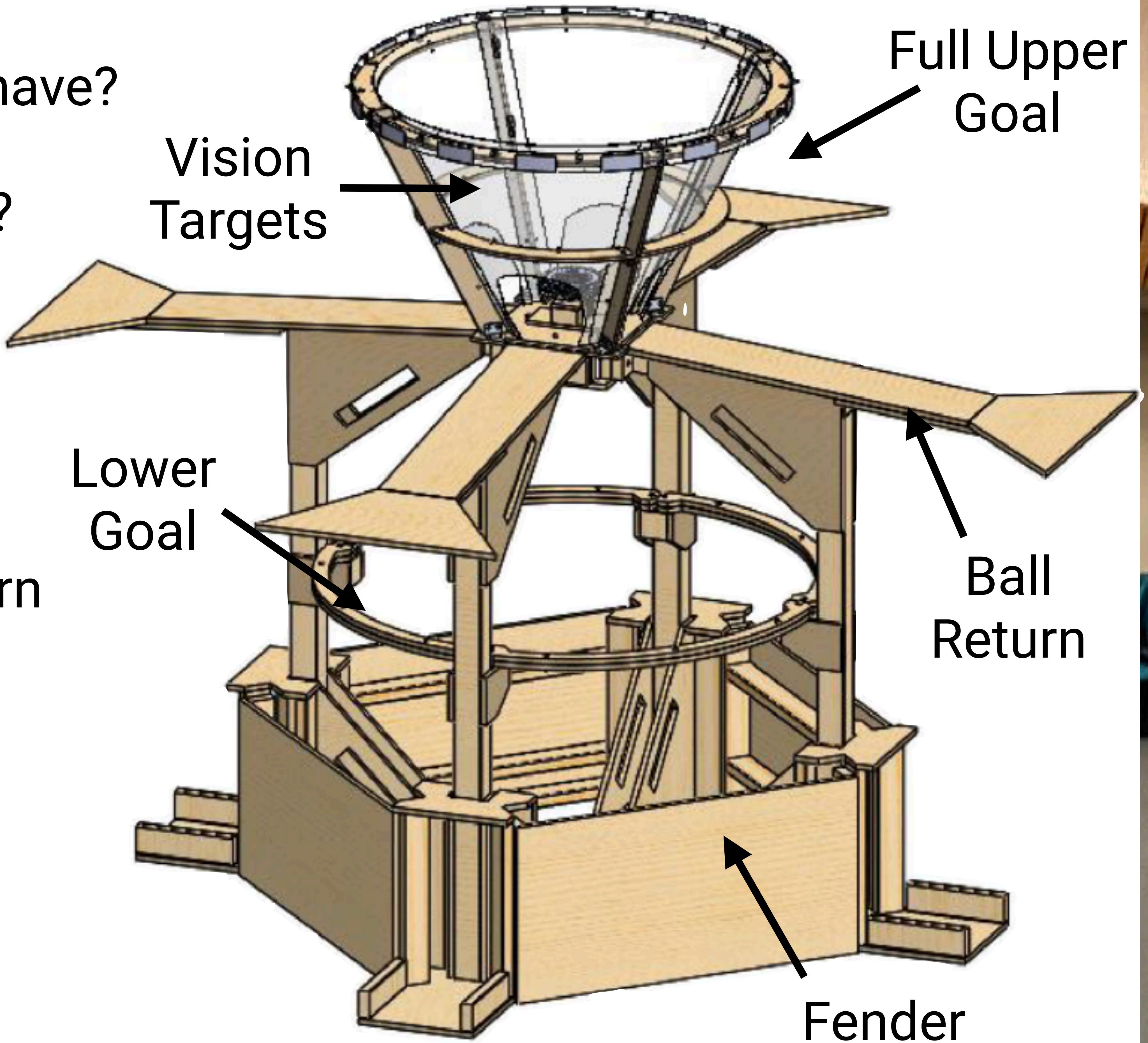
Portability

Playing Field Elements

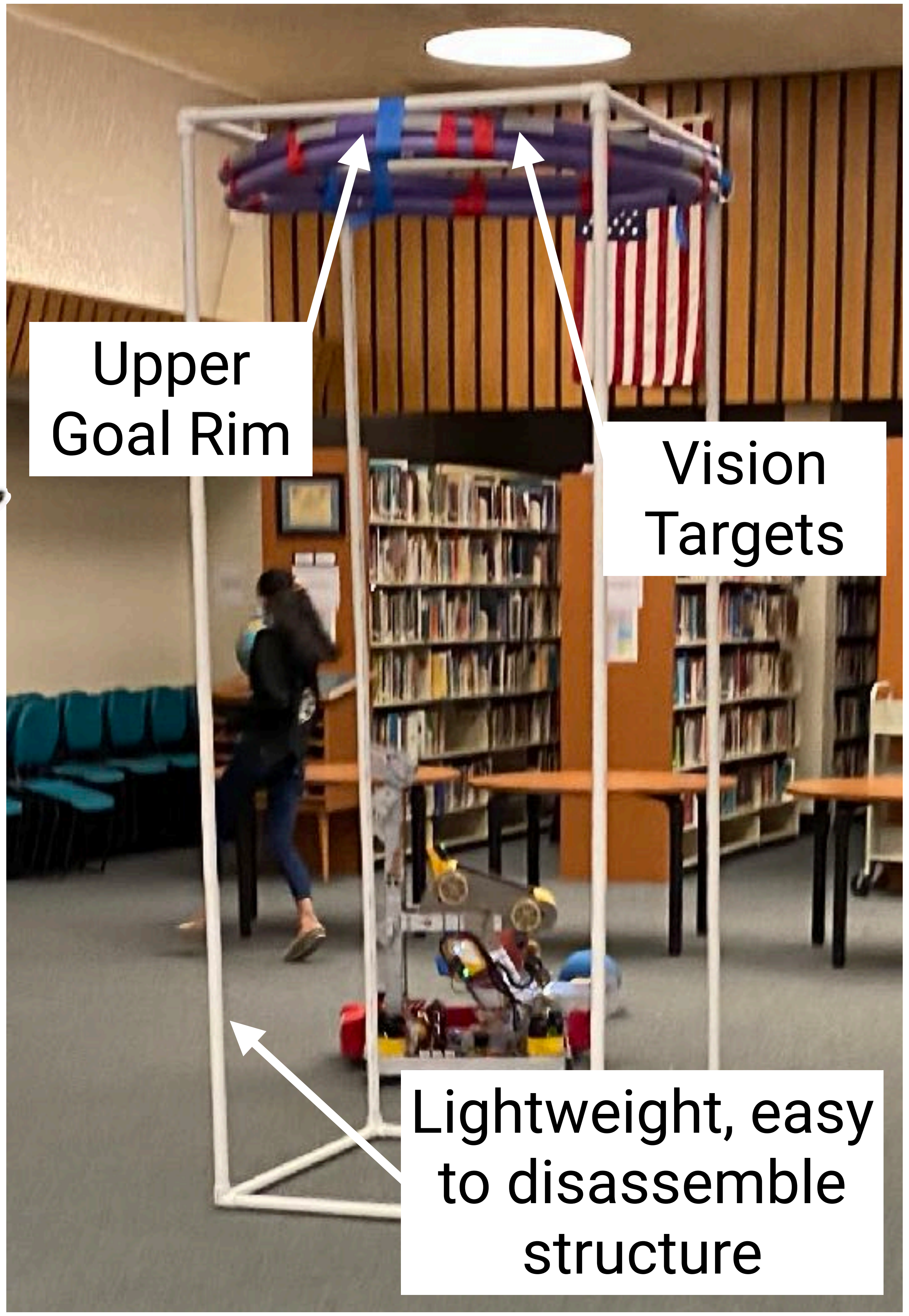
Example: 2022 Hub

- What features does the hub have?
- What do we need to practice?
  - Does vision work?
  - Does ball go into goal?
- Limitations
  - Missing bounce out
  - Obstruction from ball return
  - Aligning to Fender
  - Scoring Low

Official Wood Hub



604's Hub



Portability

Playing Field Elements

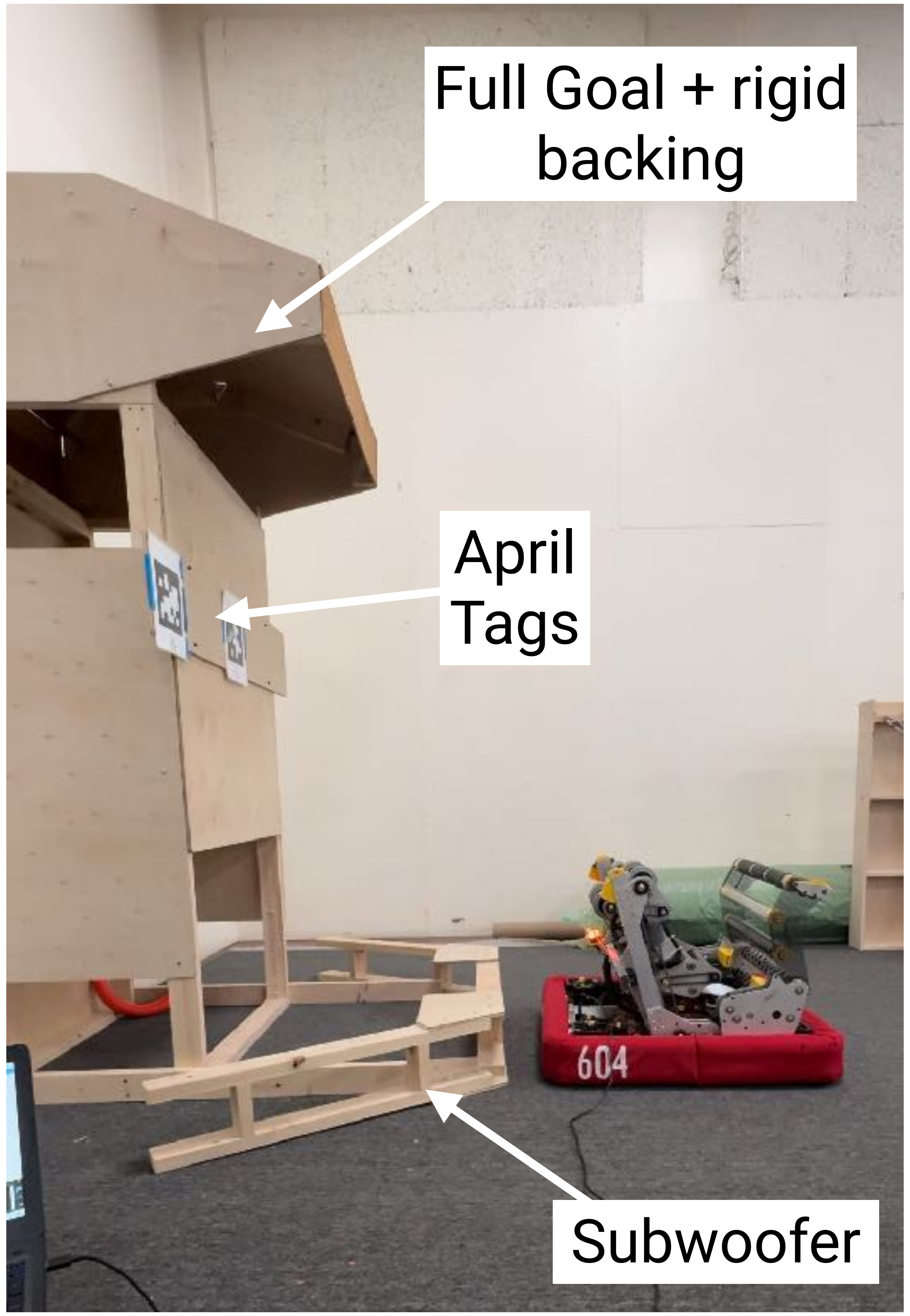
Example 2024 Speaker

- What features does the speaker have?

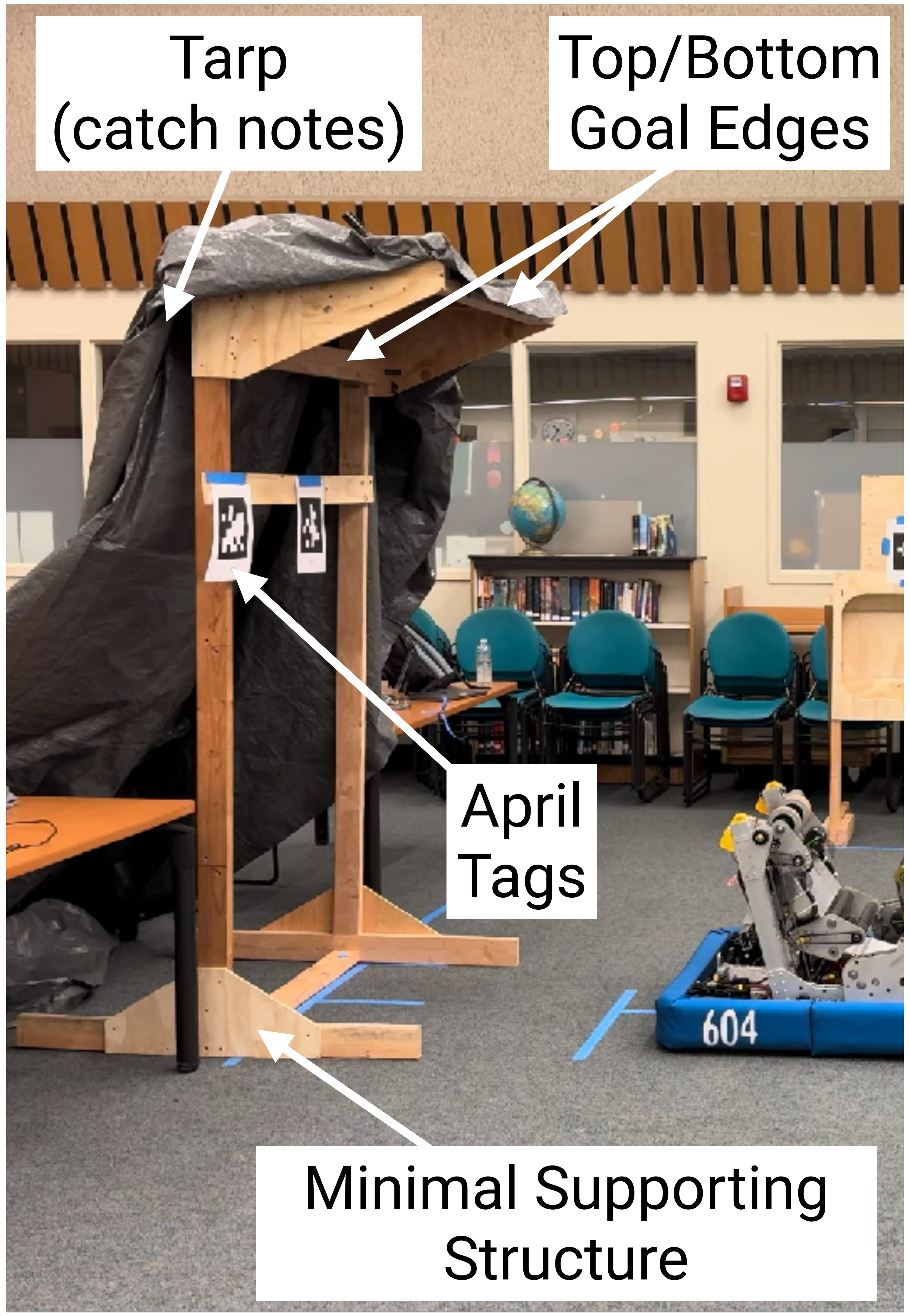
- What do we need to practice?
  - Does vision work?
  - Does note go into goal?

- Limitations
  - Missing bounce out
  - Missing alignment to subwoofer
  - Floppy April Tags (could be seen as a benefit)

Official Wood Speaker



604's Speaker



Portability

604's Build Spaces

School Robotics Room

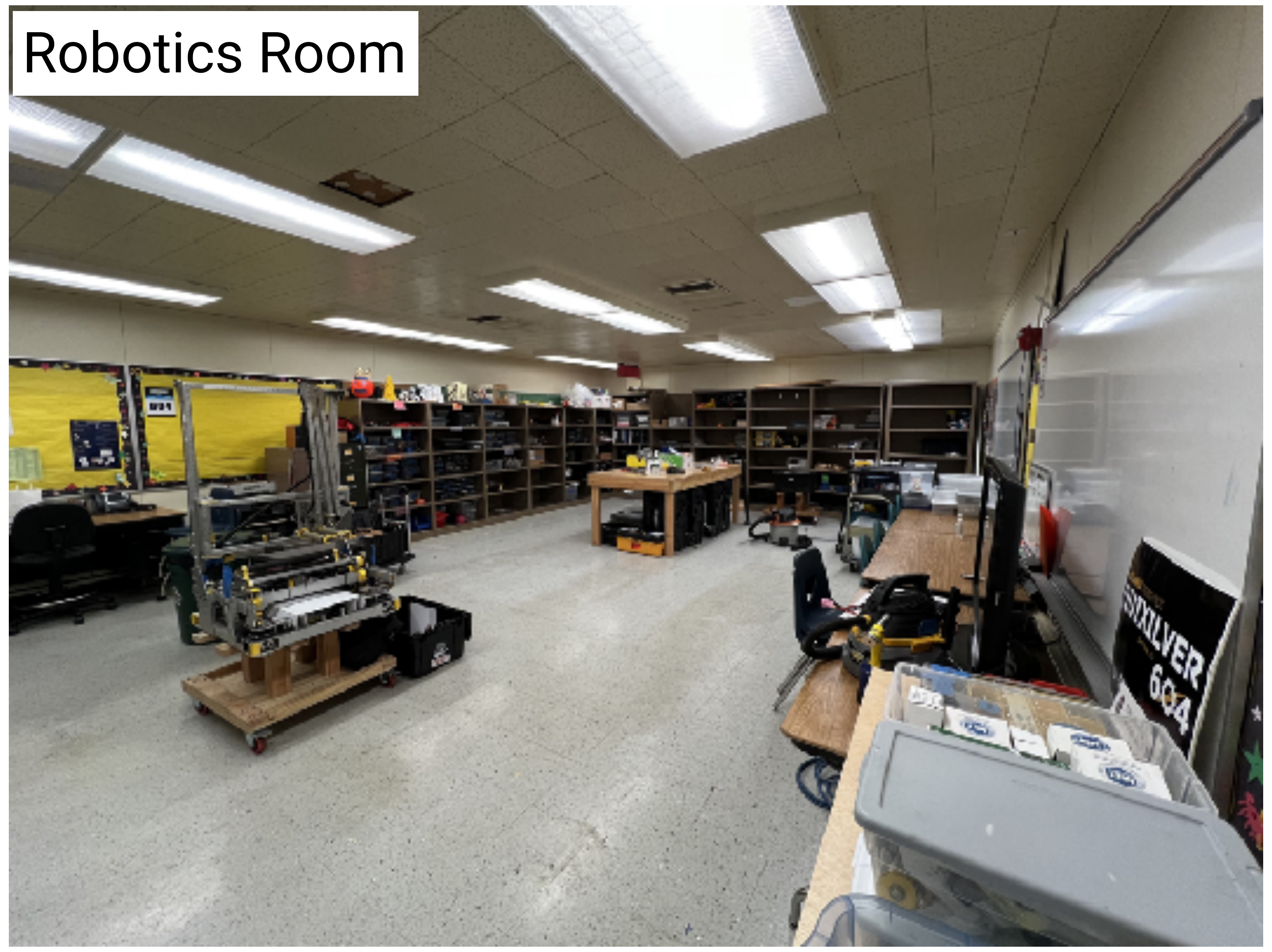
- **Availability:** Weekends (year round storage)
- **Space:** Large room with workbenches, basic tools, materials
- **Limitations:** No machine tools, availability

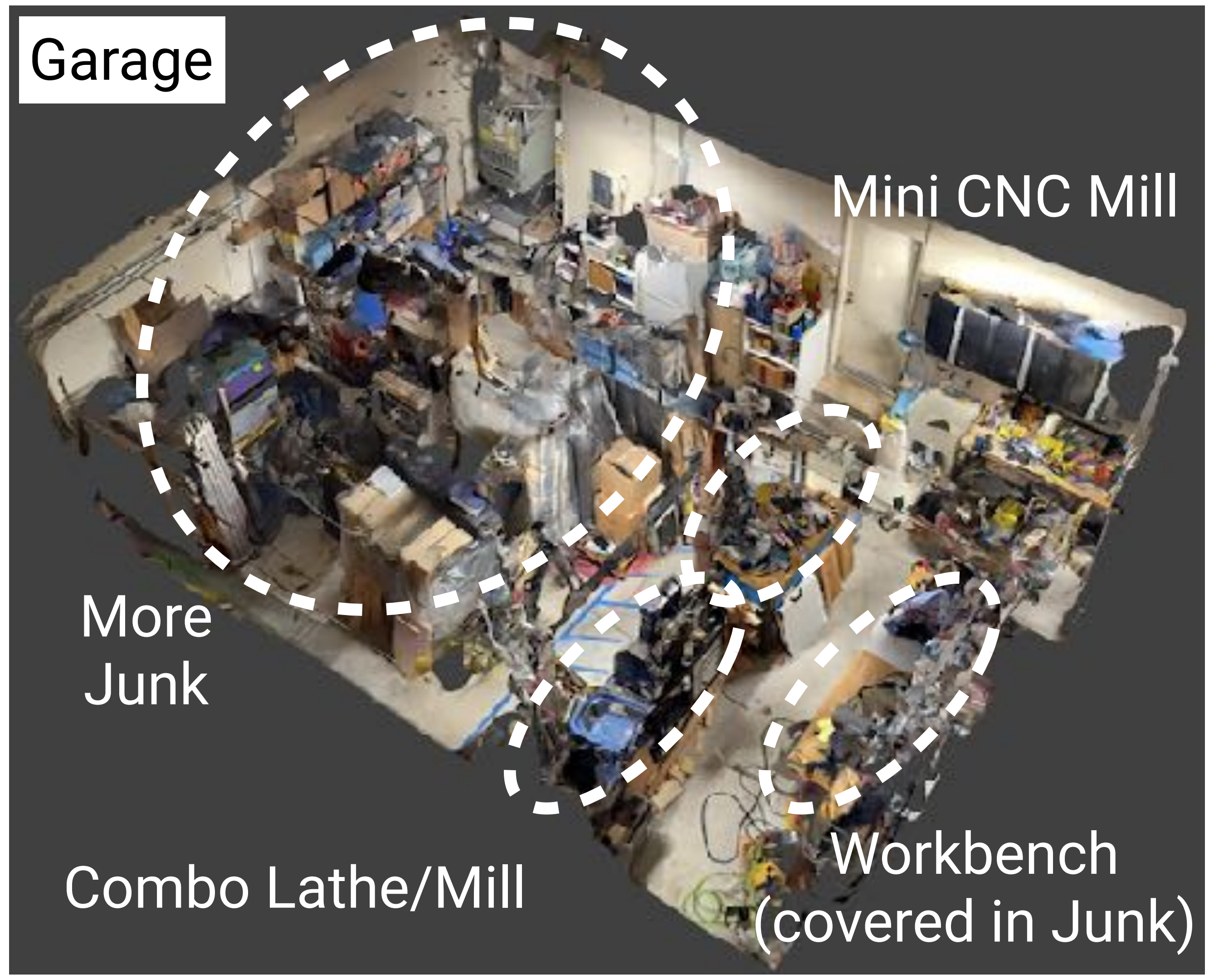
Mentor or Student House

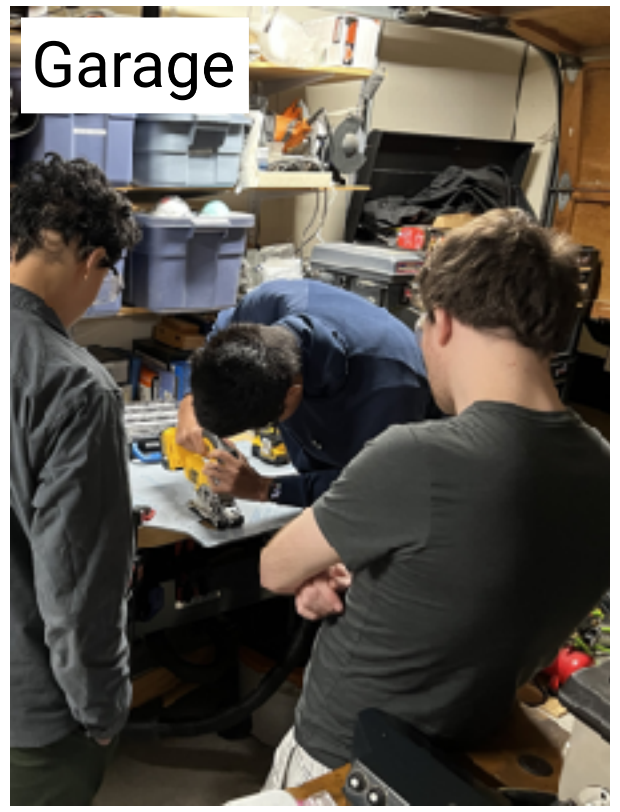
- **Availability:** Whenever someone volunteers
- **Space:** Whatever space is available (garage, maybe living room)
- **Bonus:** might have machine tools
- **Limitations:** Need to provide tools / parts / materials, junk, power failures???

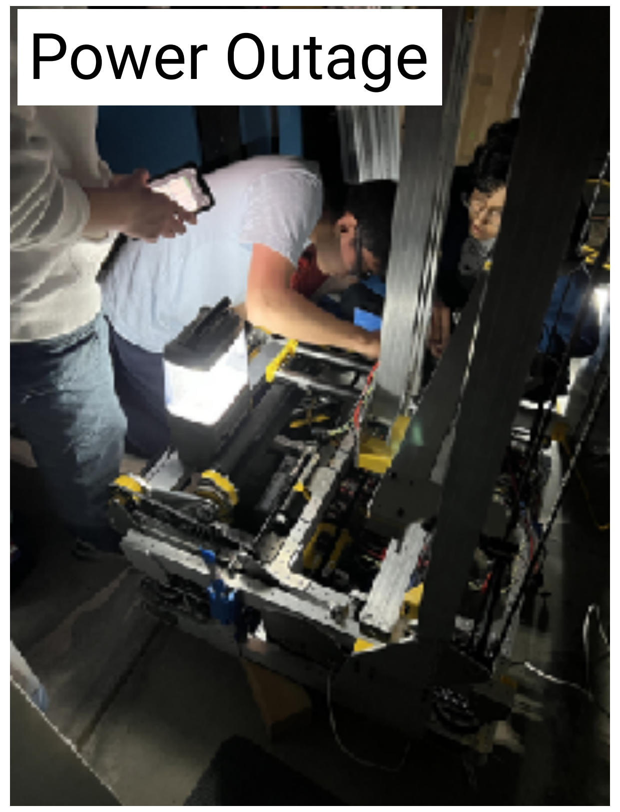
Requirement

- Move workspace between school and houses on a weekly basis









Portability

Portable Workspace

Requirements

- Tools (Hand Drill, Drill Bits, Clamps, Files, etc…)
- Parts (Hardware, COTS Parts, Material, etc…)
- Workbench
- Fast / Easy Setup
- Easy to Transport
- Affordable

Super Pits / Road Cases

- ✅ Tool Storage
- ✅ Parts Storage
- ✅ Workbench
- ✅ Easy Setup
- ❌ Need truck/trailer to transport
- ❌ Expensive to make

Photos pulled from CD thread: https://www.chiefdelphi.com/t/team-4414-hightide-pit-writeup/411862

Portability

Pit Crates

Concept

- Split road cases into 18” x 18” x 48” stacking crates

604 Pit Crates

- ✅ Tool Storage
- ✅ Parts Storage
- ✅ Workbench
- ✅ Fast Setup
- ✅ Fits in SUV
- + Palletizes for shipping
- ✅ Cheap to make (~1k)


Stacking


Cabinet Crates


Parts Bins + Battery Crates

Benches


Palletizing

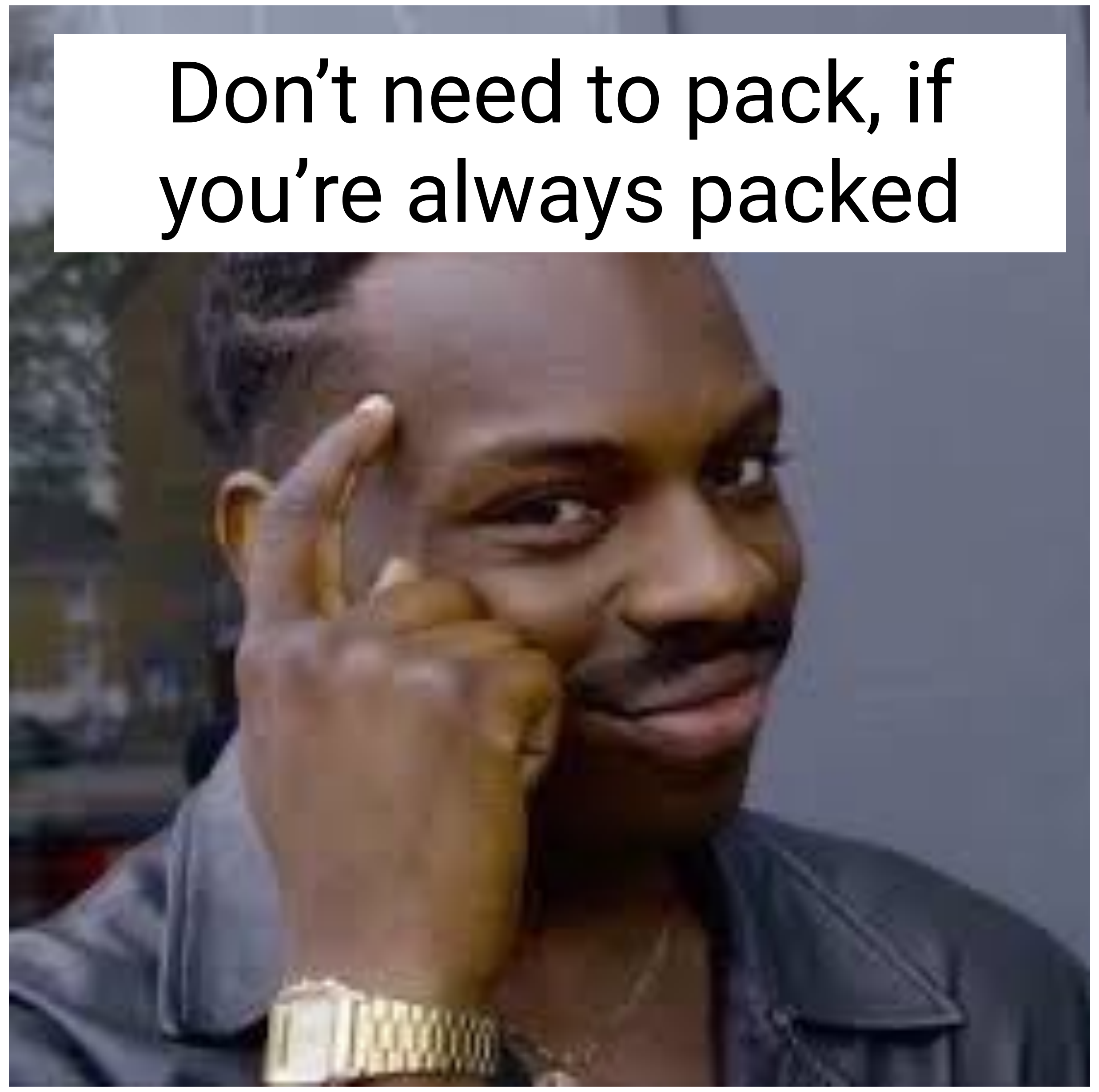

Unloading + Packing for Champs


Benches as Shipping Cover


4’x4’ Shipped to Champs

Portability
Pit Crates

Key Takeaway:
Work out of Pit Crates Year Round



- Everyone knows where things are
- Easy to move between school and garages

Simulation

Simulation

604’s Constraints & Needs

Constraints

- Limited number of physical robots
  - One robot per season
  - No multiple new off-season robots
  - Can’t break our robots
- Limited time with robot
  - Robot gets mechanically finished late
  - Practice space access only on weekends

Needs

- Teach students robot software & controls
- Enable more students to contribute to robot software
- Time efficiency when we have time with the robot
- Driver tryouts / practice

Simulation

What we gain

Accessible learning of robot code and control theory

- Visual & hands-on
- Many students in parallel
- Can tinker with a full robot at home without bringing home any hardware

Increase involvement

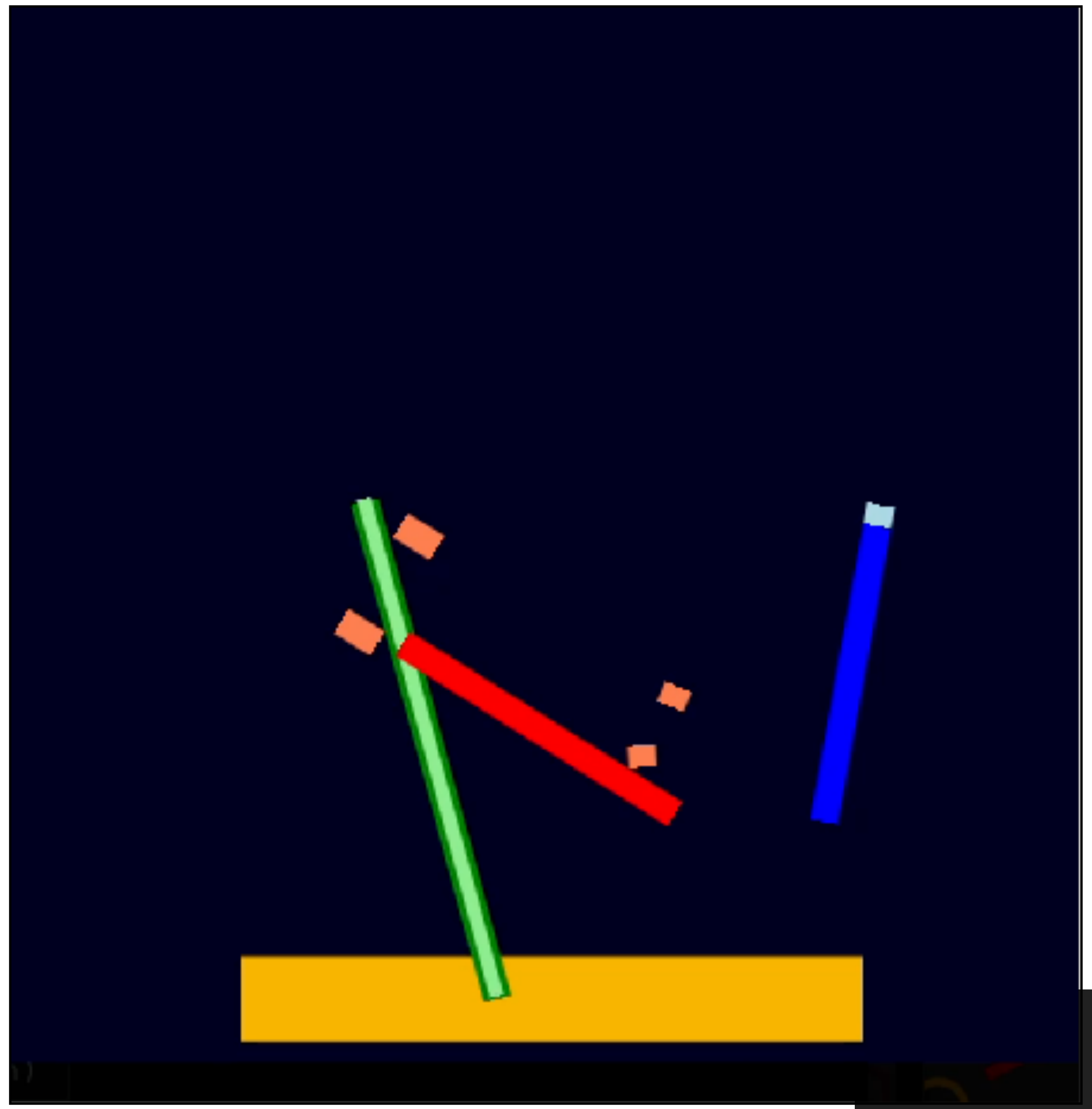
- No need to take turns with a physical robot to test code
- Lower risk of breaking the robot due to bad code

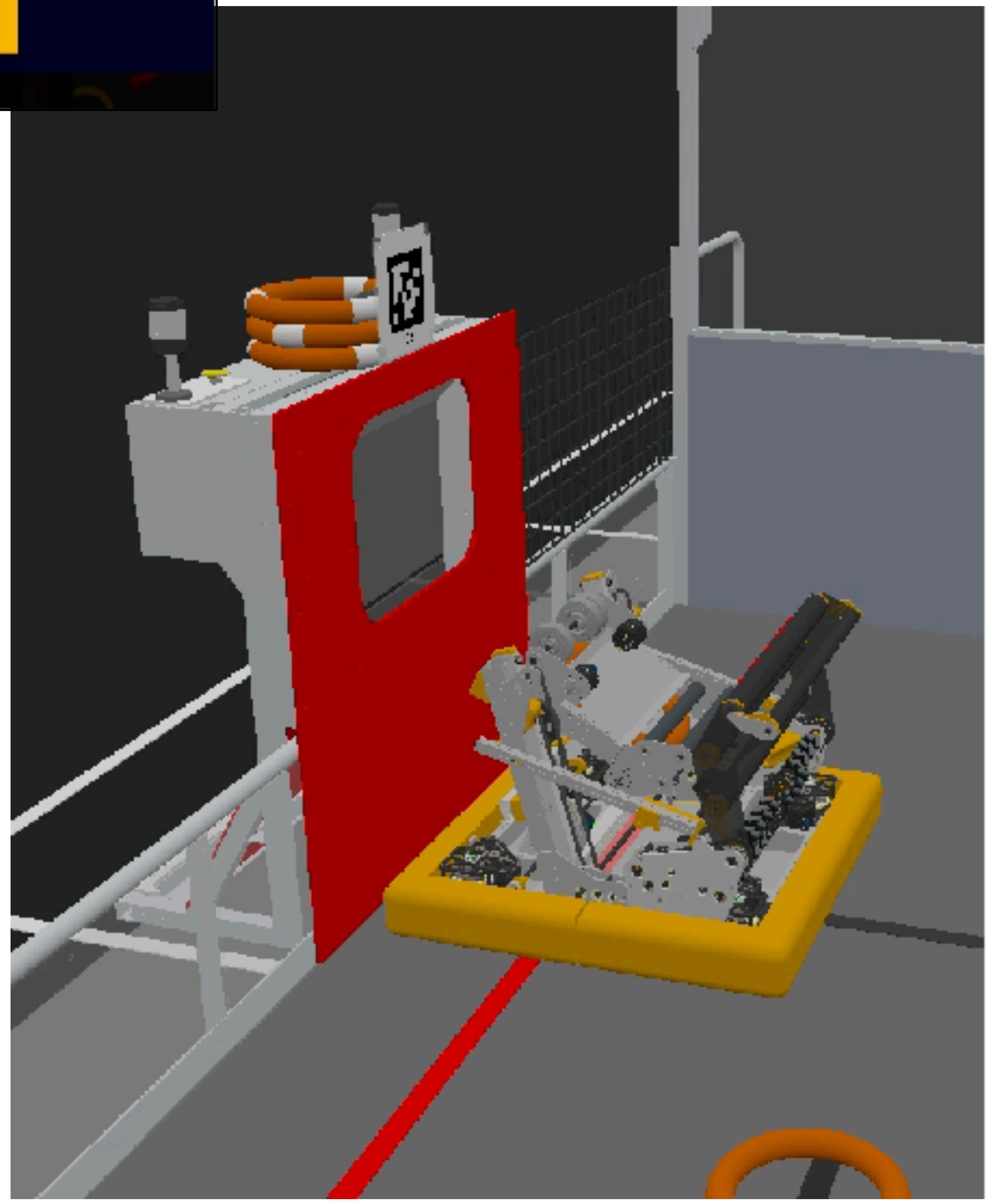
Minimize robot bring-up time

- 🔥 **Hot take** 🔥: Time between having a mechanically finished robot and a moving/scoring robot should take hours, not days

Maximize tuning and practice

- 🔥 **Hot take** 🔥: No code for new functionality should be written during in-person meetings





Robot Code Simulation

Tools Used

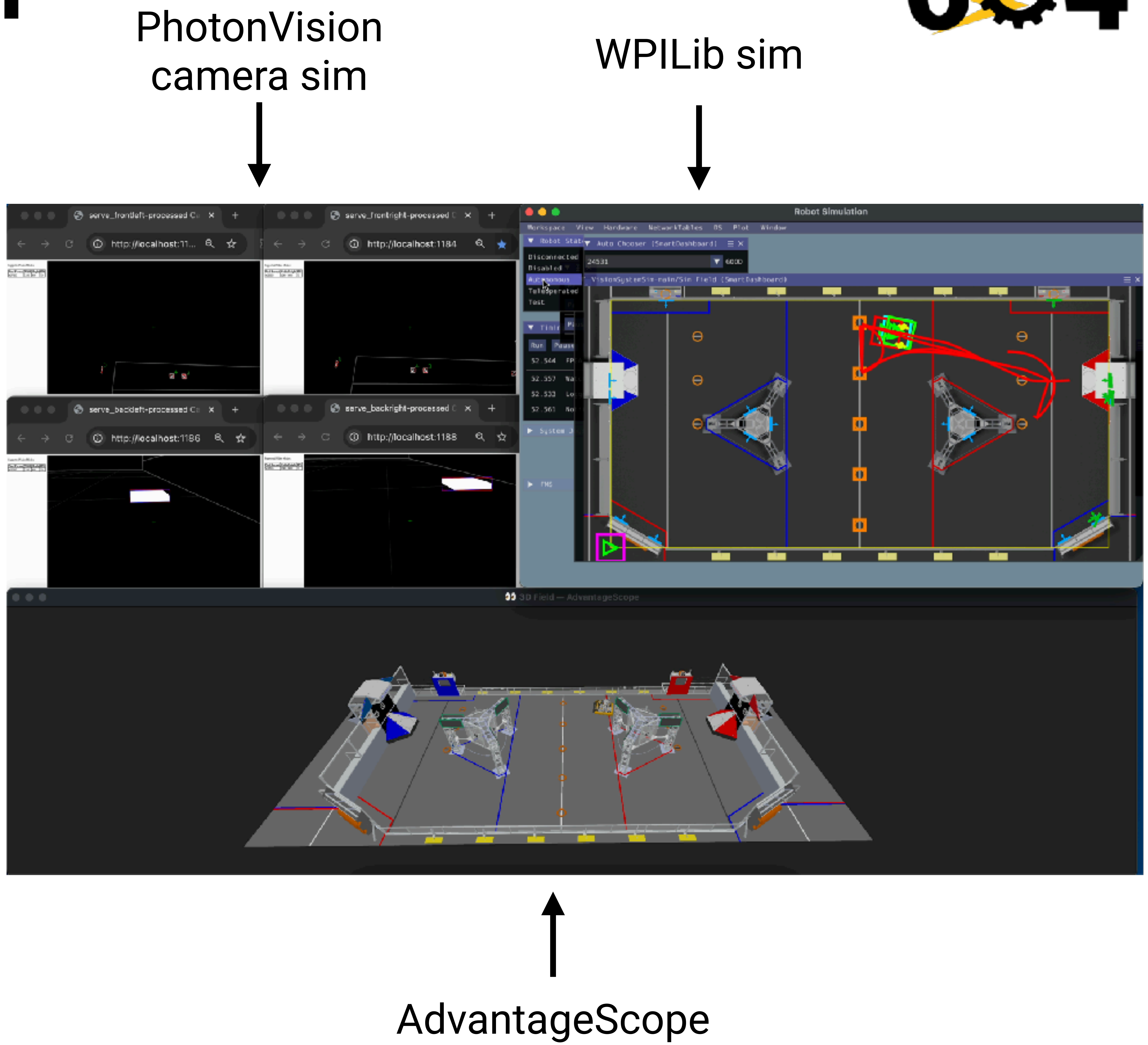
Nothing custom, a lot of resources already exist for setting these up

- WPILib physics sim
- CTRE high-fidelity motor sim
- PhotonVision camera sim
- AdvantageScope for visualization
- AdvantageKit for log resim (2024 offseason)

On 604, our entire software stack is simulated

- Camera-based latency-compensated distributed field-relative localization
- Mechanisms (Swerve, Intake, Launcher, etc.)
- Sensors (e.g. IMU, beam break, encoders)
- (Dynamic*) autos
- Game piece detection*

* Simulated and tested, but never used in competition



Robot Code Simulation

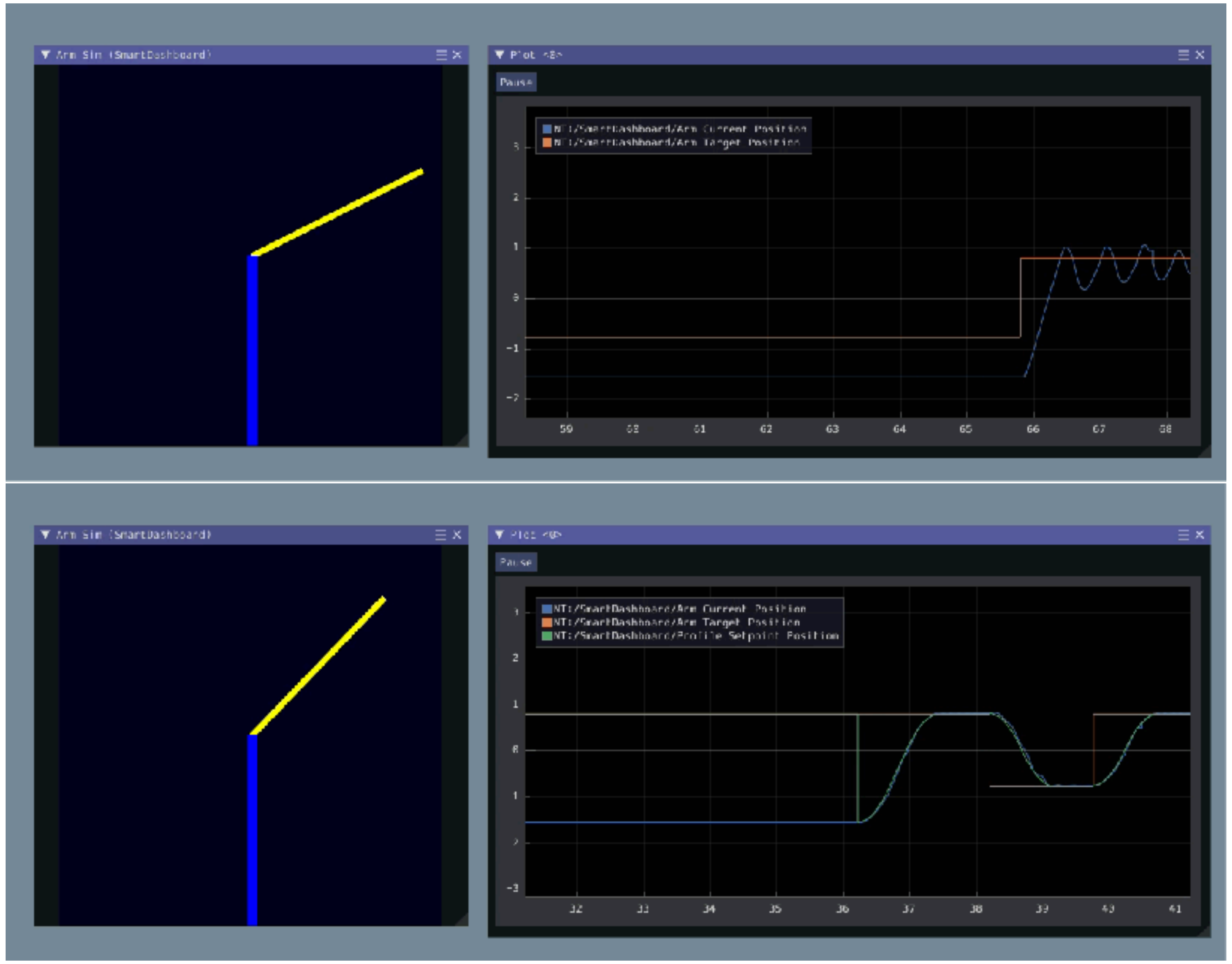
Workshop Examples

Single-jointed-arm simulation

- Feedback control (bang-bang, PID)
- Feedforward control / motion profiling
- Build intuition for tuning / let students try crazy things without breaking hardware

Previous year's robot code with everything except for simulation logic deleted

- Brainstorm commands, subsystem interfaces, etc.
- Implement basic robot functionality
- Test in simulation
- Run on real robot at the end

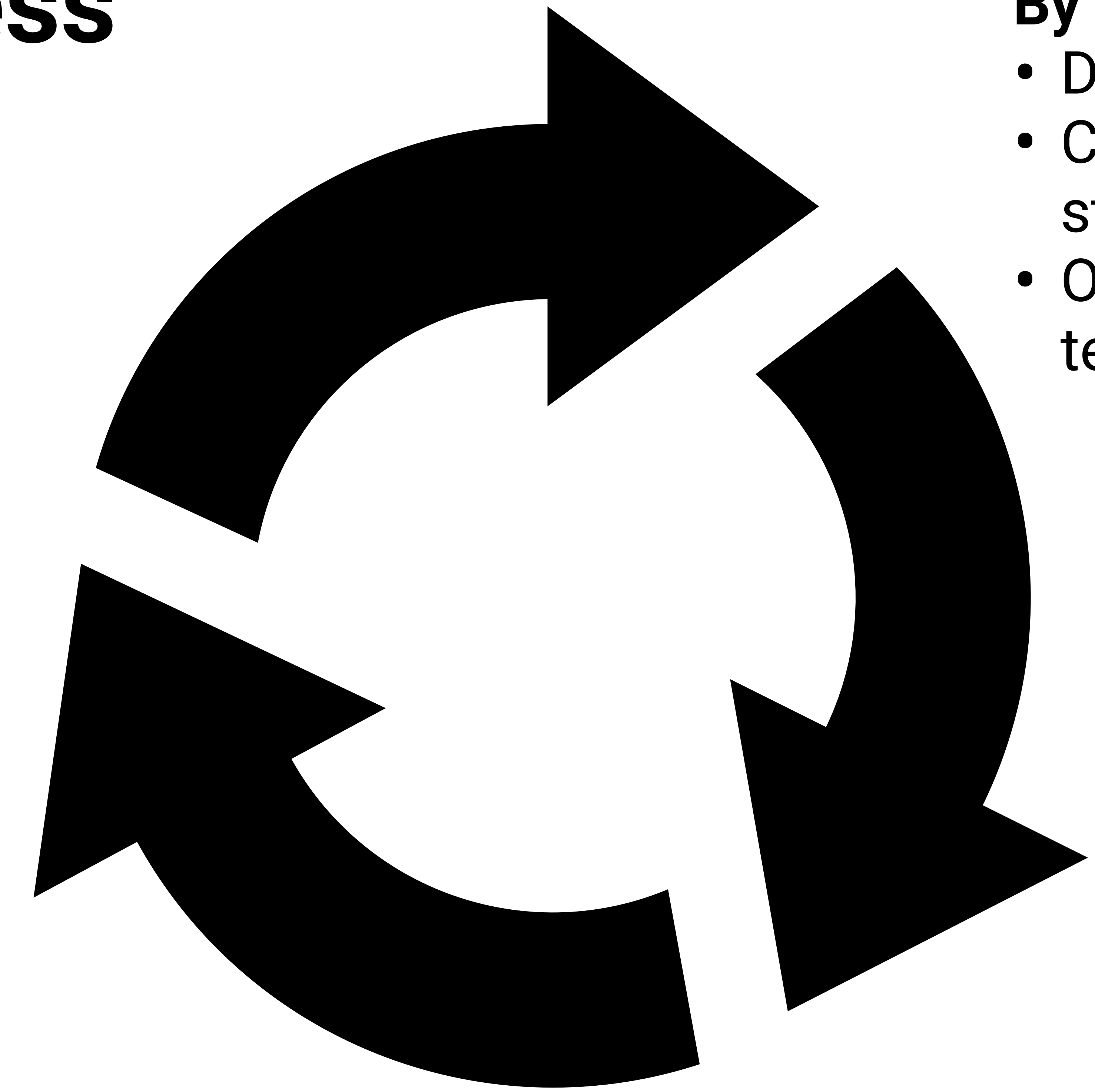


Mechanism2D viz + plotting within WPILib simulator

Robot Code Simulation

Build Season Process

Weekdays
- Develop features in simulation
- GitHub Pull Requests (PRs) for code review and feedback



By Friday Night
- Demonstrate new feature functionality in sim
- Code quality for each PR is in a “ready to merge” state, minus tuning parameters
- Only code that meets the above criteria will be tested over the weekend

Weekend in-person meetings
- Test and tune each new feature, merge new features that work into the main software branch
- After new features are merged, the rest of the time is dedicated to drive practice*
- Some time allotted to attempt to fix minor bugs
- Major bugs & missing features are addressed Saturday night, or during the next week

* Driver and software team continuously communicate expectations for how features are supposed to work; even if a feature is not yet implemented or not yet perfect, the driver practices assuming the feature works as intended in order to build the correct muscle memory

Driving Simulator

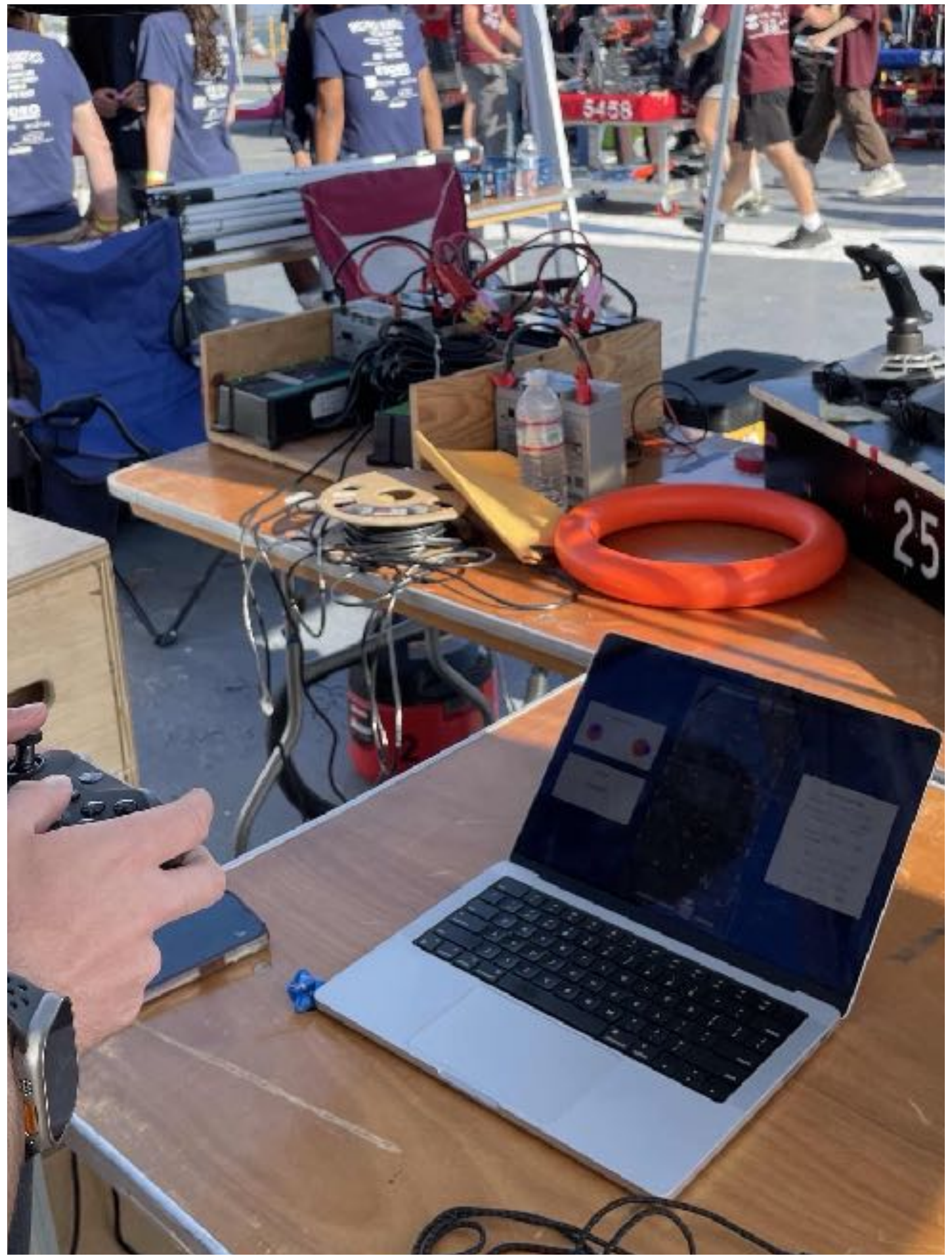
Goals

For driver practice

- Enable building of muscle memory without access to the robot
- Develop coordination between driver & operator
- Provide a way to warm up at competitions

For offseason driver tryouts

- Provide more equitable opportunity to learn the controls (robot access, runtime, battery limitations)



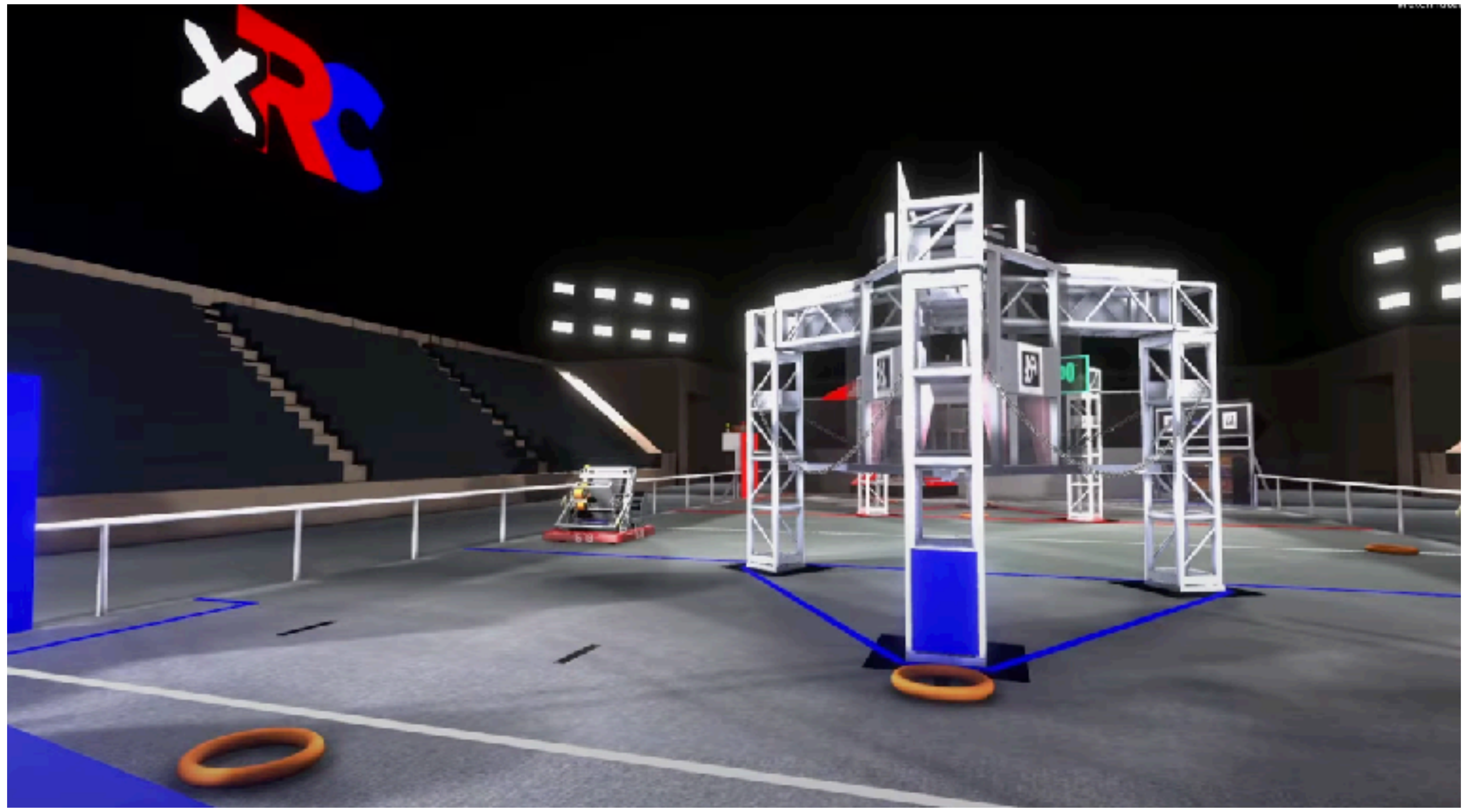
Driving Simulator

Why not use existing tools?

Existing simulators
- xRC
- MoSimulator
- etc.

Unrealistic physics develops bad habits
- e.g. “bang-bang” control when driving instead of smooth stick motions

Controls don’t match our real robot
- Joystick deadbands & scaling
- Automated features (e.g. auto aim)
- Some controls can be customized, but some are still limited (e.g. toggle vs. hold behavior)



Driving Simulator

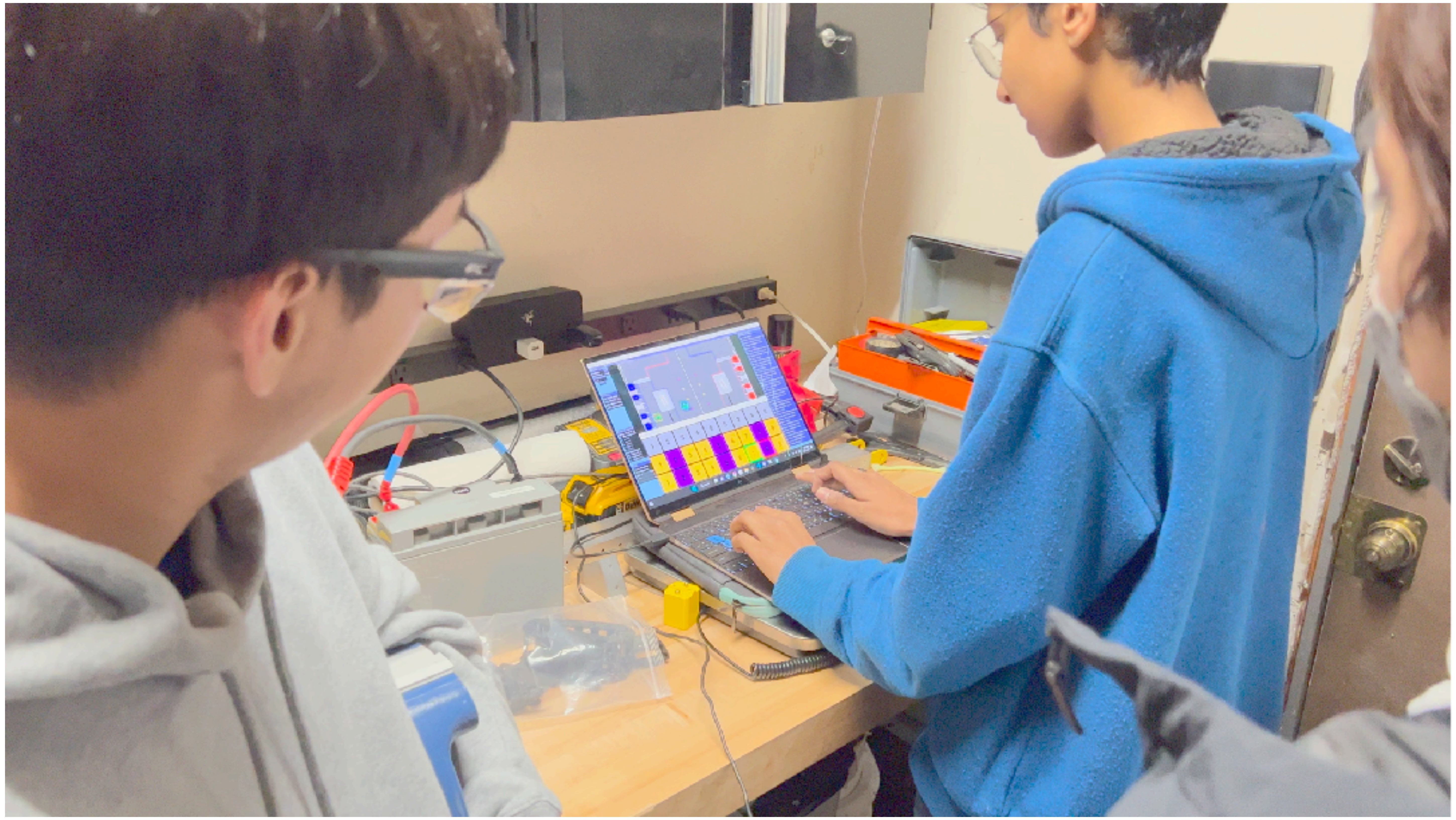
Robot Code vs. Unity Sim

- Robot Code Sim
  - ✅ Already available
  - ✅ Exactly matches real robot logic
  - ❌ Tedious set up for each student (need to download many dependencies)
  - ❌ Laggy on some computers
  - ❌ Requires additional collision checking logic
- Unity Sim (WebGL)
  - ❌ Needs to be made separately
  - ❌ Must re-create real robot logic
  - ✅ Visit web page, plug in controller, and start driving
  - ✅ Runs smoothly on most computers
  - ✅ Collision checking is built into the game engine

Driving Simulator

2023 2D Robot Code Sim

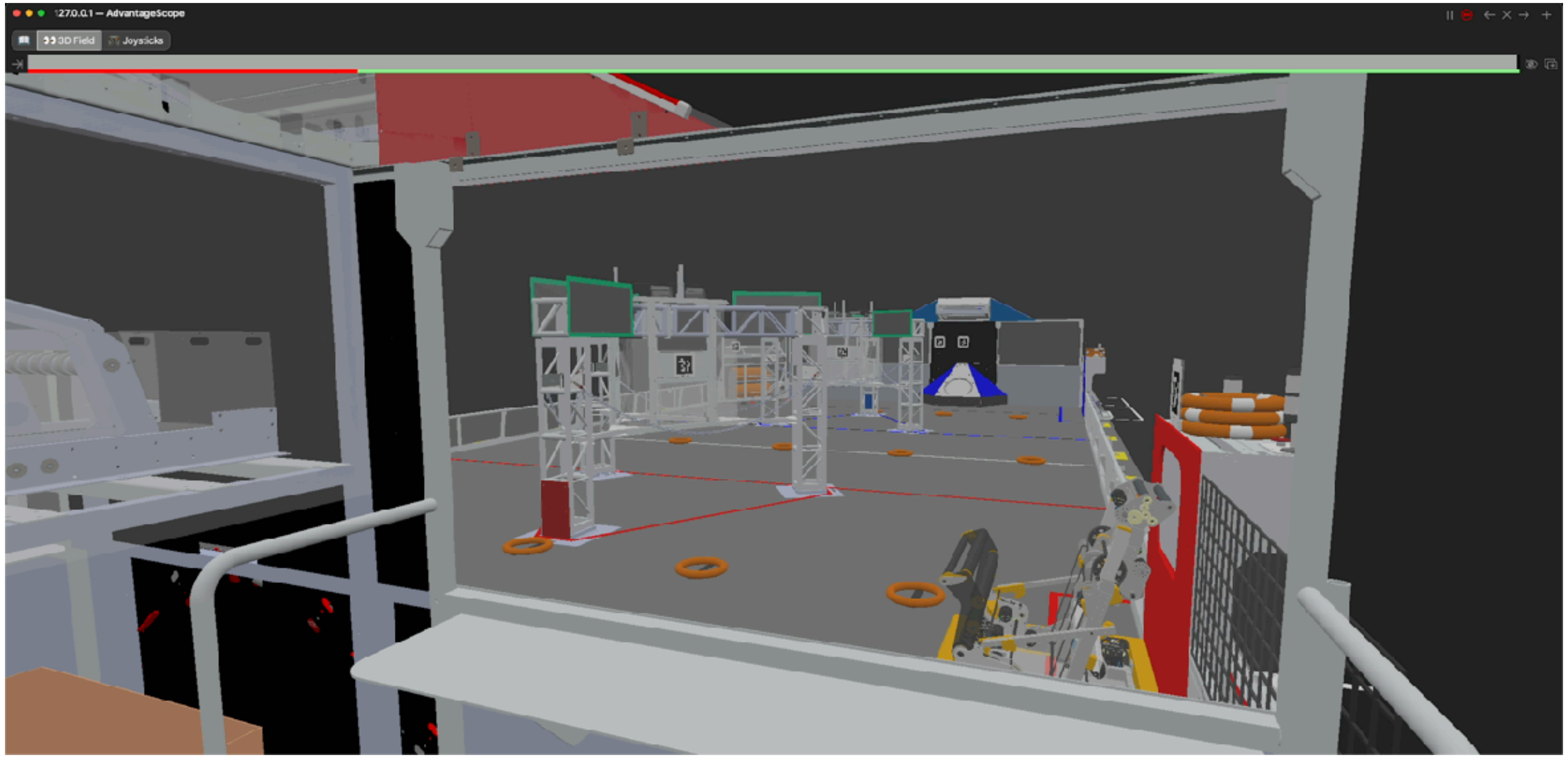
- Control scheme: operator selects next scoring position, driver triggers scoring action
- Zero real-robot scoring practice until practice day at our first regional
- Driver & operator used 2D robot code sim to practice coordination



Driving Simulator

2024 3D Robot Code Sim

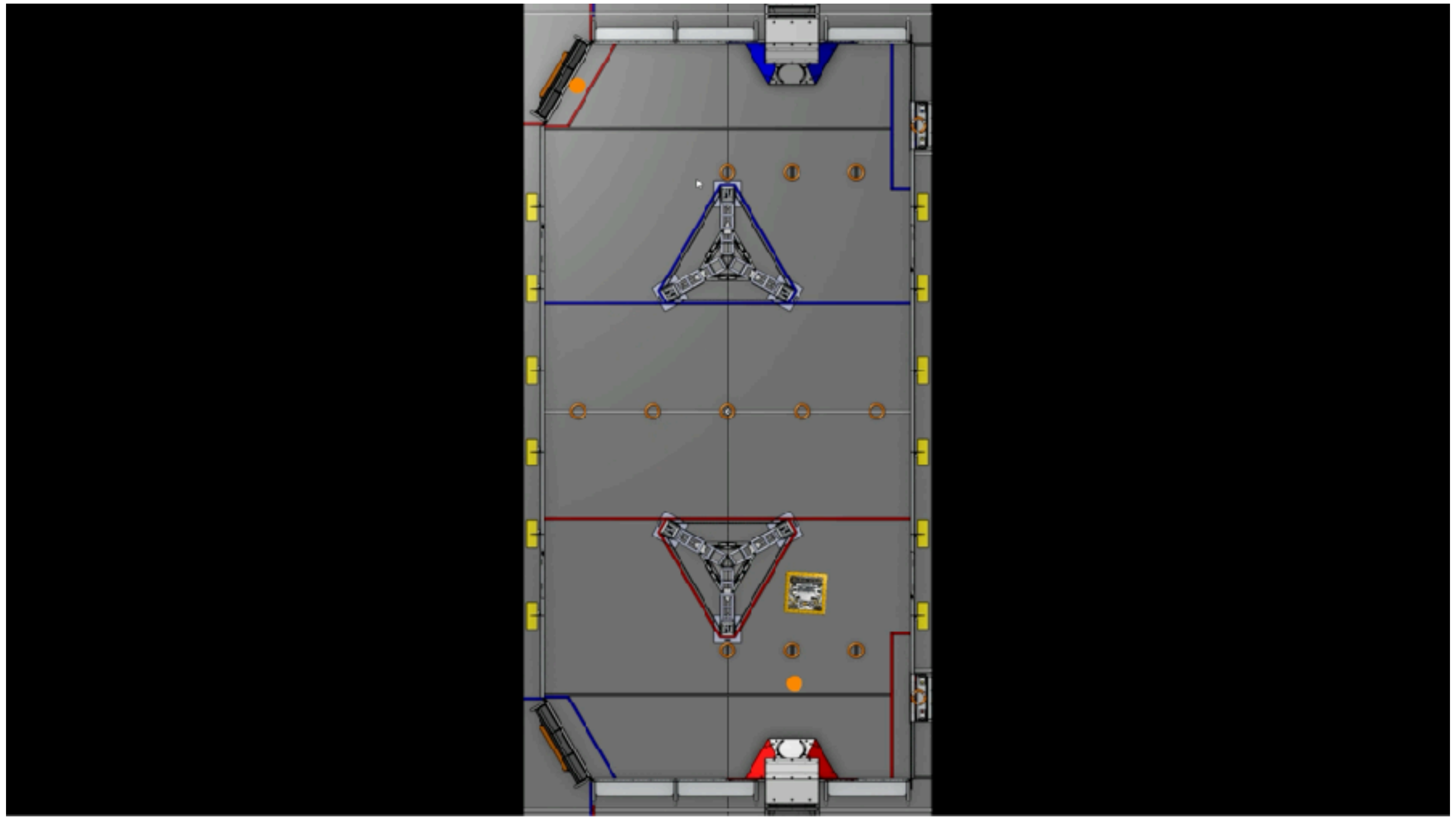
- Not much extra work on top of existing robot code sim
- Added collision checking with stage & field perimeter
- Didn’t get to implement visual feedback for shooting Notes
- Used in the offseason as part of tryouts and practice

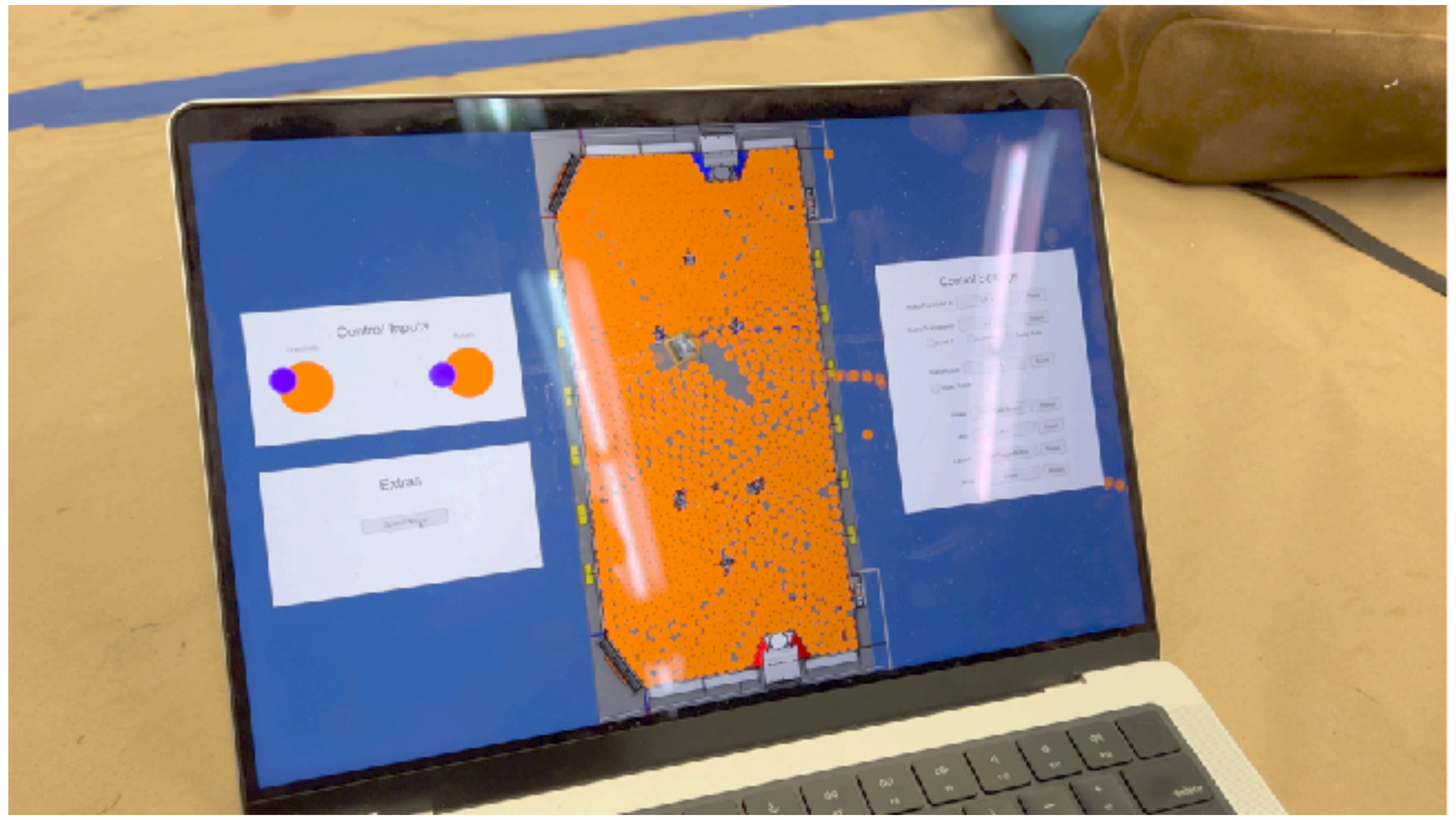


Driving Simulator

Unity Sim

- Web-based — plug in controller and start driving
- 2D top-down view
- Primarily used to build muscle memory for coordinating button presses
- Plans to make 3D in the future





Simulation
Limitations

More exciting for students to see code running on a real robot vs. in sim

Missed learning opportunities from experiencing bad code breaking the robot
- Build season is not the time for catastrophic failures
- Provide students more opportunities to fail during the off season