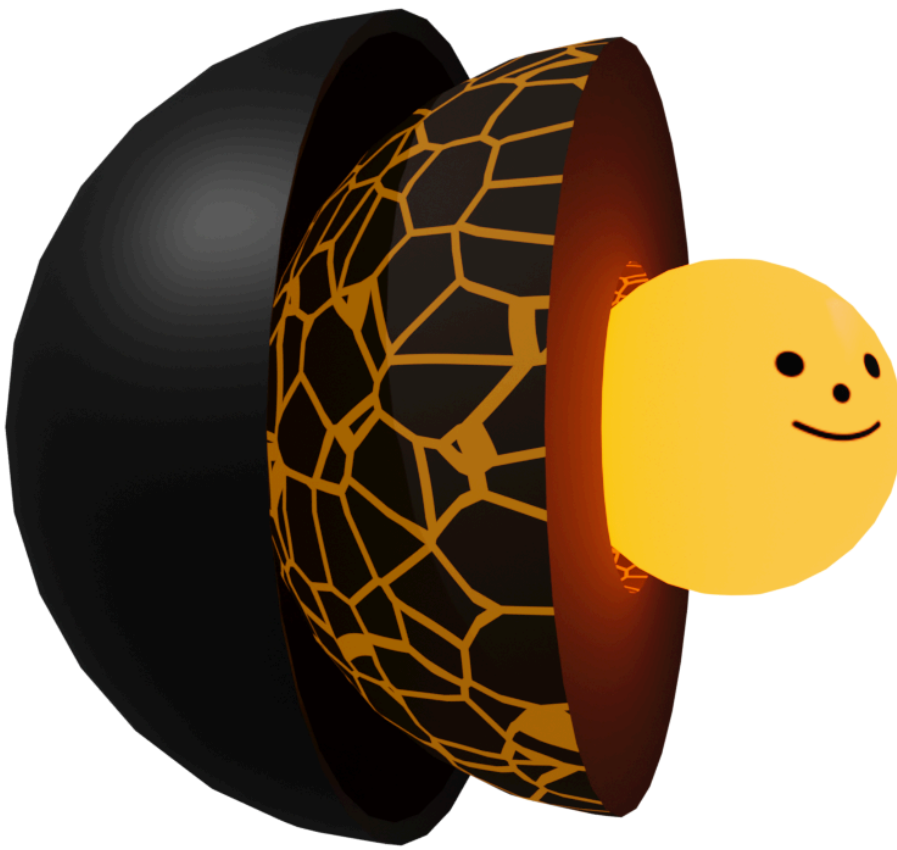
RIT VEXU Software Engineering Notebook

2023-2024



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Overview

Core API

All of the robot code we use is built on top of our own custom library, called the Core API, which itself is built on top of the official VEX V5 library. This API contains template code for common subsystems such as drivetrains, lifts, flywheels, and odometry, and common utilities such as vector math and command-based autonomous functions. This code remains persistent between years and is constantly updated and improved. The library can be found at ***github.com/RIT-VEX-U/Core***

The Core codebase is abstracted in a way that allows for simple use during a hectic build season, and creates a solid foundation for future expansion. Subsystems are divided into layers following an object-oriented approach to software development.

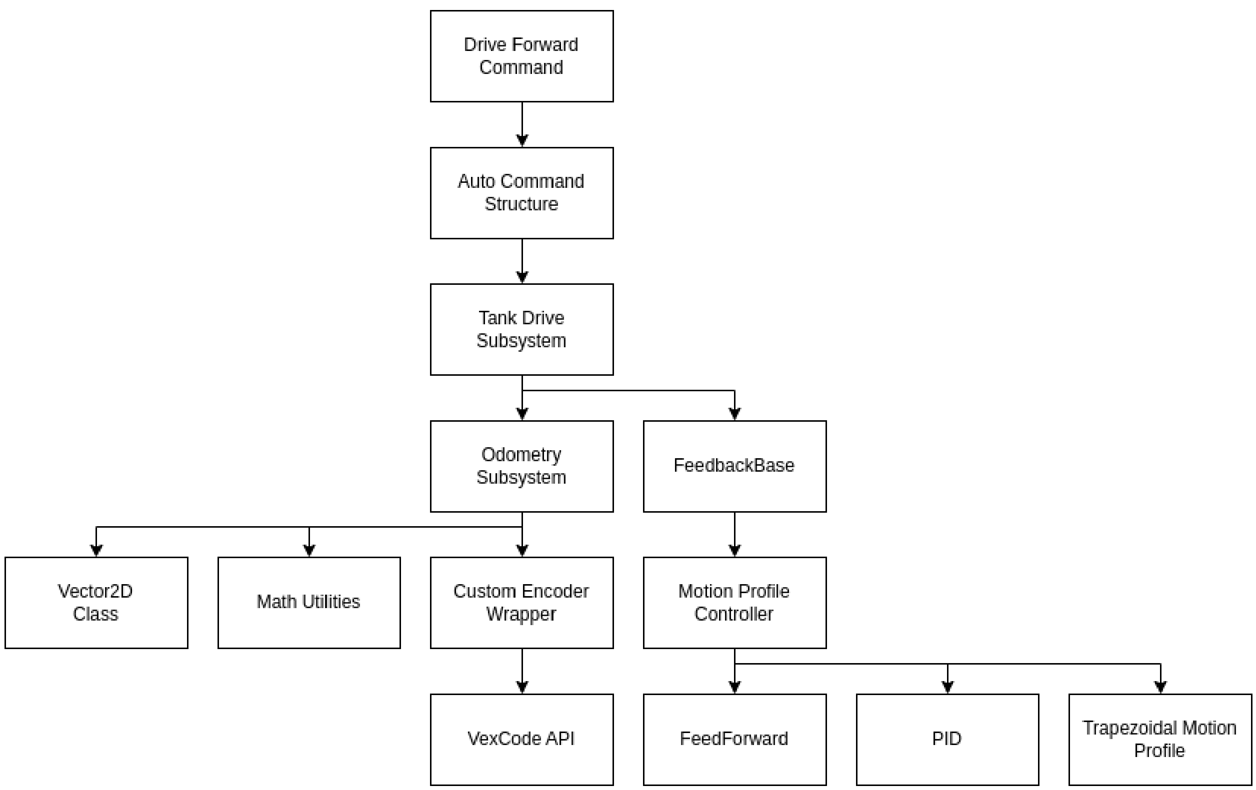


Figure 1 - Example of Object-Oriented Programming

Open Source Software

The Core API is under the MIT open-source license, and is open for other teams to use and improve upon via pull requests. This system was modeled after the Okapi library from the Pros ecosystem, and offers similar functionality for the VexCode ecosystem. Teams that use this API are also encouraged to open source their software.

Project Structure

During the season, there are three repositories (repos) that are actively developed. Two repositories for the two competition robots, and one for the Core API. Development and code building occurs in the robot repos, and any changes to shared code (drivetrain, math utilities, major subsystems) are merged with the Core repo. This method reduces redundant code and development time.

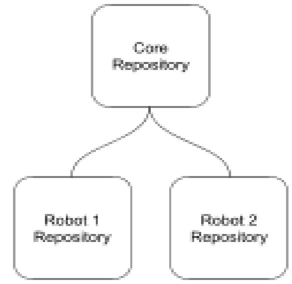


Figure 2 - Project Structure

Git Subrepo

The Core API uses a unique type of version control called Git Subrepo (github.com/ingydotnet/git-subrepo). This allows users to simply clone the repository into an existing VexCode project to have instant access to all the tools. It also allows users to instantly receive updates by pulling from the main branch, and makes sharing code between two robot projects easier with git code merges.

Before choosing Subrepo, the team experimented with using Git Submodules to incorporate the Core API into projects. This however made Core development cumbersome and difficult for anyone unfamiliar with Git submodules specifically. Subrepo made inter-project merges more streamlined, and simplified development.

Github Project Board

In order for our software team to collaborate together with these projects, we use the Github Projects kanban-style project board. This allows us to create and assign tasks, link it to a repository and additionally notify the assigned programmer through a slackbot.

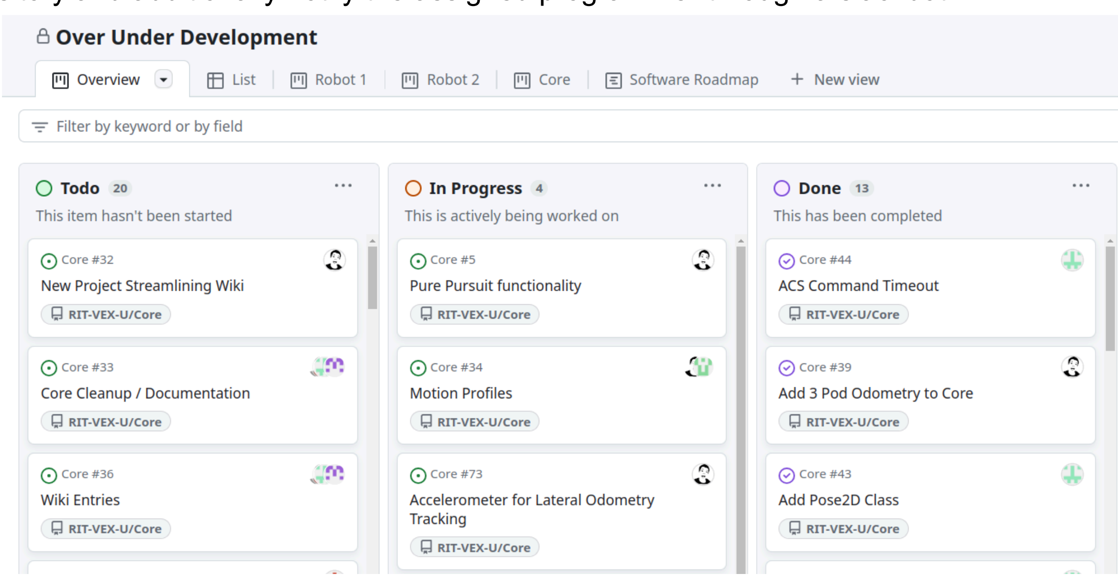


Figure 3 - Software Project Board

Github Actions

This year, our team enhanced our workflow by integrating GitHub Actions into our software development process. One notable addition was an action to build our C/C++ code in the appropriate Vex environment. This automated process involves a series of steps, including checking out the repository, downloading and unzipping the Vex Robotics SDK and toolchain, and compiling the code using a Makefile. A key feature of this GitHub Action is its ability to send a Slack notification to our team channel whenever a build fails, ensuring prompt awareness and response. Furthermore, it helps maintain code integrity by preventing the merging of pull requests with failing builds. This complements our other GitHub Action for building Doxygen documentation and deploying it to GitHub Pages, allowing for seamless documentation and code management. This systematic approach aligns with our commitment to maintaining a neat, organized, and efficient engineering process.

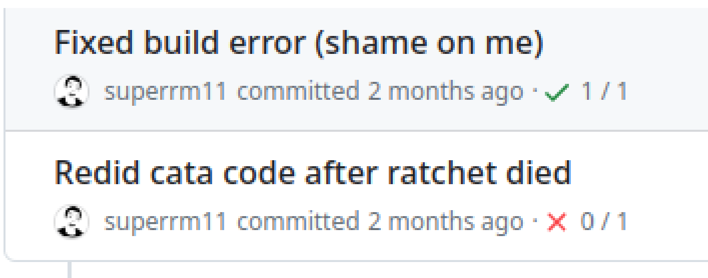


Figure 4: Continuous Integration directly improves the quality of our code.

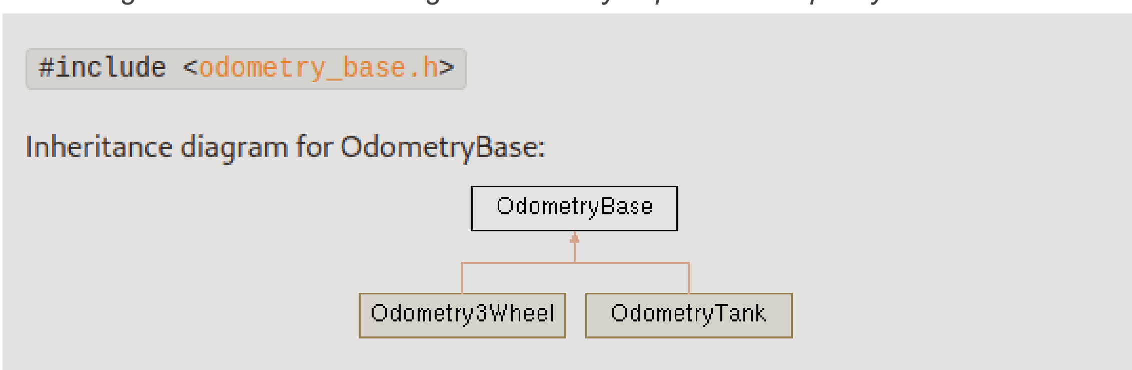


Figure 5: Automatically generated documentation.

Auto-Notebook

Alongside the automatic documentation, whenever Core is updated or we manually trigger it, a Github Action copies the reference manual, exports the most up to date version of our written notebook document, stitches them together, and deploys to a webpage. This is publicly available for any person wishing to see our software development process. The most valuable effect, though, is automating most of the formatting work for our notebook, work that used to require a team member to use valuable pre-competition time to sit down, append, format and export the notebook.

Clang-Tidy

In an effort to improve the quality, reduce headaches, and make our code easier to read, write, and understand, we enabled many more warnings than what is supplied with the default Vex project Makefile. These warnings deal with uninitialized variables, missing returns, and other simple code errors that nonetheless have the tendency to introduce tiny, hard to track down bugs. However, sometimes these warnings do not explore deep enough and another tool must be used. We integrated clang-tidy, a c++ linter developed by the clang compiler project, to inspect our code. With a simple switch of a variable in the Makefile, we run clang-tidy during builds which gives many insights into the code that plain compiler warnings do not. Though it does increase compilation times, it tells us about code that is bug prone or poor for performance and tests many other checks developed and validated by the wider C++ community.

Wiki

Whenever a new feature is added to Core, we create a Wiki page on the Core Github repository that provides documentation on what the function does, how to use it, and some examples of how it can be used. This documentation is easily accessible as it can be found online within the Core repository itself. This allows for new members to get acquainted with Core faster and easier than before. This allows us to speed up our training process and allow new members to start developing sooner rather than later. In addition it provides us and anyone using Core great documentation that not only goes into method signatures and descriptions, but also detailed explanations of what different methods, classes or functions do.

Opcontrol

This class provides two ways of driving the robot with a controller: Tank drive and Arcade drive. Drivers can choose what they're most comfortable with.

Tank Drive - The left joystick controls the left-side motors, and the right joystick controls the right-side motors

Arcade Drive - Acts somewhat to how modern racing video games are controlled. The left joystick controls the forward / backward speed, and the right joystick controls turning left / right.

Both functions also have an optional parameter called `power`, and refers to how the joystick is scaled to the motors. The higher the power is, the more control you have over low-speed maneuvers. Because the scaling is non-linear, it may feel weird to those who aren't used to it.

Method Signatures

```
void drive_tank(double left, double right, int power=1);
void drive_arcade(double forward_back, double left_right, int power=1);
```

Usage Examples

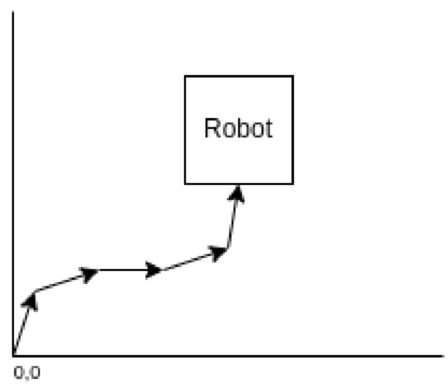
```
drive_system.drive_tank(controller.Axis3.position() / 100.0, controller.Axis2.position() / 100.0);
drive_system.drive_arcade(controller.Axis3.position() / 100.0, controller.Axis1.position() / 100.0);
```

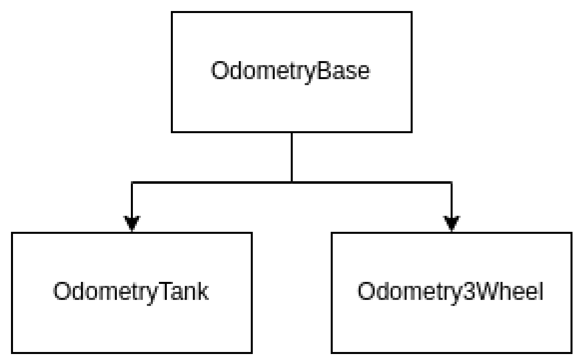
Figure 6: A screenshot of the Core Wiki

Core: Fundamentals

Odometry

In order for the robot to drive autonomously, it needs to know where it is, and constantly monitor changes to sensors. The Odometry subsystem takes inputs from encoders, and using vector math and previous position data, calculates the position and rotation of the robot on the field as a point in space (X, Y), and heading (deg).





The Odometry subsystem is broken down into an OdometryBase class, which controls the asynchronous behavior and getters/setters, and OdometryTank and Odometry3Wheel classes, which both extend OdometryBase and implement a two-encoder algorithm and a three-encoder algorithm, respectively.

GPS + Odometry

In order to fit an 8-motor drivetrain into the 15" size requirement, the robots could not fit non-powered odometry wheels, leaving only the drive encoders to be used for position tracking. This isn't ideal, since sudden changes in acceleration and wheel slippage can easily cause the tracking to drift a substantial amount. To combat drifting, we looked to the GPS sensor for localization.

The GPS sensor uses a tag-based approach for localization, using a coded strip around the perimeter of the field to estimate position. Between pose estimates, the integrated IMU provides inertial information to estimate changes in position and heading for a constant flow of data, presumably using some sort of onboard Kalman filter. The pose (X, Y, Heading) data is sent back to the Brain over the smart port. In addition, the GPS provides a "quality" value, which is a percentage that increases when the camera can see a large amount of tape, and decreases when the camera is blocked and the IMU detects change in position over a period of time.

To properly characterize the GPS sensor, X/Y/Heading data points were gathered at different positions around the field, facing different headings. The following graphs show the data points on the 12' x 12' field grid. Distance error (in inches) to the actual measurements is shown by color.

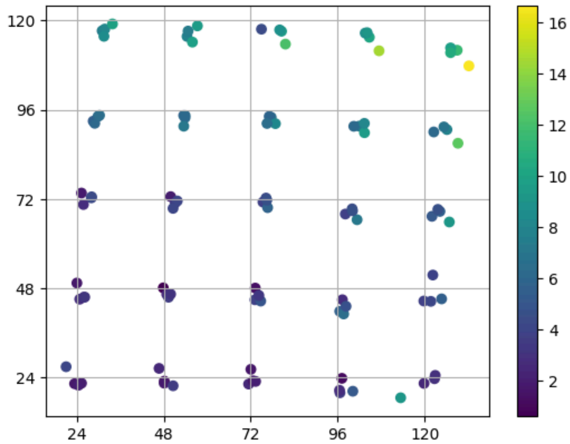


Figure 7 - Raw Data Points

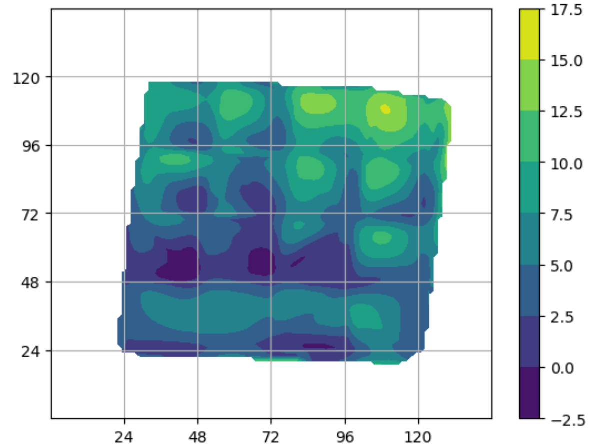


Figure 8 - Error Heat Map

There were some other errors with the GPS sensor, including issues localizing the robot when the sensor could not see enough of the coded tape. To take full advantage of the GPS sensor's localization capability, we'd need a way to perform sensor fusion alongside traditional ground-based odometry. To do this, a complementary filter was chosen - a filter that mixes two sets of data based on a proportional scalar *alpha* (α). the equation for a complementary filter is shown below:

$$out = \alpha * s_1 + (1 - \alpha) * s_2$$

where s_1 is *sensor 1*, s_2 is *sensor 2*, and alpha scales between the two.

To calculate alpha, first the X,Y position of the sensor and heading is taken into account. Since the robot will generally have a more accurate position when it's close to the wall and facing away from it, the following formula will report a score between 0 and 1 for the filter:

$$\alpha = \left(\frac{\vec{c} - \vec{p}}{||\vec{c} - \vec{p}||} \bullet \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix} \right) * \frac{||\vec{c} - \vec{p}||}{||\vec{c}||} * q$$

where $\vec{c}$ is the constant vector of a point in the center of the field (x=72in, y=72in), $\vec{p}$ is the robot's position as a vector (x, y), θ is the robot's heading, and x,y is again the robot's position (0 to 144 inches). The left side is the dot product of the normalized vector pointing from the robot to the center with the direction the robot is facing (gives 1 when the directions are aligned and -1 when opposite smoothly changing in between), and the right side is the sensor's distance to the center as a scalar percentage of the distance from corner to corner (between 0 and 1). Finally, q is the GPS's reported quality. We then remap this from the range [-1, 1] to [0, 1] when we do our mixing.

Drivetrain

A drivetrain class has two functions: To control the robot remotely, and autonomously. In the Core API, the TankDrive class allows the operator to control the robot using Tank controls (Left stick controls the left drive wheels, right controls the right), and Arcade controls (Left stick is forward / backwards, right stick is turning). This means drivers can tailor their controls to whichever feels more natural.

Tank Drivetrain

Brake Mode

A VEX driver has many things to keep track of during a match. From game element position, match load status, and partner robot condition there is a great deal going on. Defense is another layer on top of the mental load of playing the game. To ease this burden, we implemented a brake mode on our drive train. It is a multi-modal system that can either bring the robot to a stop or hold the robot in a specific location on the field. We use the motion profiles we developed for auto programming to decelerate the robot when requested and use our auto driving functions to hold the robot's position. We implement a smarter form of position holding than just motor braking as we can return to the exact location on the field. Additionally, we combine our deceleration control with position holding such that we do not immediately “lock the brakes” and skid away thus losing the position we attempt to hold and making driving incredibly difficult.

Autonomous Driving

For autonomous driving, the TankDrive class has multiple functions:

- drive_forward():
    - Drive X inches forward/back from the current position
    - Signature: drive_forward(double inches, directionType dir, double max_speed=1
- turn_degrees():
    - Drive X degrees CW/CCW from the current rotation
    - Signature: turn_degrees(double degrees, double max_speed=1)
- drive_to_point()
    - Drive to an absolute point on the field, using odometry
    - Signature: drive_to_point(double x, double y, vex::directionType dir, double max_speed=1);
- turn_to_heading()
    - Turn to an absolute heading relative to the field, using odometry
    - Signature: turn_to_heading(double heading_deg, double max_speed=1)

Generally, it is better to use drive_to_point and turn_to_heading to avoid compounding errors in position over relative movements. These functions implement the FeedbackBase class, so any control loop can be used to control it.

Drive To Point

The defining feature of a drive to point function is the ability for a robot to calculate a relative direction and distance between its own position and the target position, and navigate to it using tuned control loops. The steps taken for our implementation are listed below.

1 - Gather information

To drive towards a specific point, the robot must know the change in angle between the robot's heading and the target, and the distance to the target. To get this, we first grab the robot's current position and heading and create a positional difference vector between this and the new point.

```
pose_t current_pos = odometry->get_position();
pose_t end_pos = {.x = x, .y = y};

point_t pos_diff_pt =
{
  .x = x - current_pos.x,
  .y = y - current_pos.y
};

Vector2D point_vec(pos_diff_pt);
```

Using this information, grab the distance to the target (using a function in the Odometry subsystem). An issue with the pure distance between points is that it does not represent how far the robot has to travel to be considered "on target" in the control loop. In order to properly reach its target, the robot should report its "aligned distance", and ignore the lateral error, as per Figure 9. This should only hold true when the robot is close to the target, or inside a given radius that is tuned by the user.

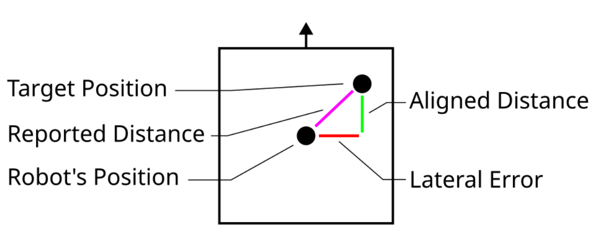


Figure 9 - Distance Modification

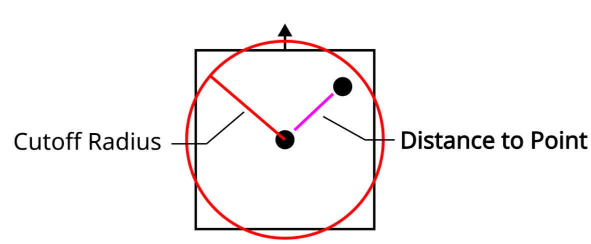


Figure 10 - Correction Cutoff Circle

```
double dist_left = OdometryBase::pos_diff(current_pos, end_pos);

if (fabs(dist_left) < config.drive_correction_cutoff)
{
 dist_left *= fabs(cos(angle * PI / 180.0));
}
```

The next data needed is the difference in angle between the robot's current heading and the vector between the robot's position and the target. This is calculated by using the arctangent of the difference vector, and subtracting it from the robot's current heading. The angle is then wrapped around 360 degrees.

```
double angle_to_point = atan2(y - current_pos.y, x - current_pos.x)
                        * 180.0 / PI;
double angle = fmod(current_pos.rot - angle_to_point, 360.0);
if (angle > 360)
 angle -= 360;
if (angle < 0)
 angle += 360;

double heading = rad2deg(point_vec.get_dir());
double delta_heading = 0;
if (dir == directionType::fwd)
 delta_heading = OdometryBase::smallest_angle(current_pos.rot, heading);
else
 delta_heading = OdometryBase::smallest_angle(current_pos.rot
                 - 180, heading);
```

The last piece of information needed is whether the robot should be moving forwards or backwards. Since the distance is calculated as $\sqrt{x^2 + y^2}$, the sign is lost when squaring. Re-implement the sign based on the angle and initial driving direction.

```
int sign = 1;
if (dir == directionType::fwd && angle > 90 && angle < 270)
 sign = -1;
else if (dir == directionType::rev && (angle < 90 || angle > 270))
 sign = -1;
```

2 - Setting Control Loops

In this section, the robot takes the above information and sets its feedback loops. Since the function takes in a FeedbackBase abstract class, any feedback can be used to drive the robot's correction and linear movements. The most common situation is a trapezoidal motion profile for linear distance with PD for heading correction. Once the robot is close enough to the target point, the correction feedback is ignored to avoid issues with last-minute heading changes.

```
correction_pid.update(delta_heading);
feedback.update(sign * -1 * dist_left);

double correction = 0;
if (is_pure_pursuit || fabs(dist_left) > config.drive_correction_cutoff)
{
 correction = correction_pid.get();
}

double drive_pid_rval;
if (dir == directionType::rev) {
 drive_pid_rval = feedback.get() * -1;
} else {
 drive_pid_rval = feedback.get();
}

double lside = drive_pid_rval + correction;
double rside = drive_pid_rval - correction;

lside = clamp(lside, -max_speed, max_speed);
rside = clamp(rside, -max_speed, max_speed);

drive_tank(lside, rside);
```

Finally, when the linear feedback reports its on target, stop, return and report that the movement is over.

```
if (feedback.is_on_target())
{
 if (end_speed == 0) {
   stop();
 }
 func_initialized = false;
 return true;
}
```

Pure Pursuit

Pure Pursuit is a method of autonomous robot driving that allows the robot to autonomously drive through a set of waypoints without stopping and turning.

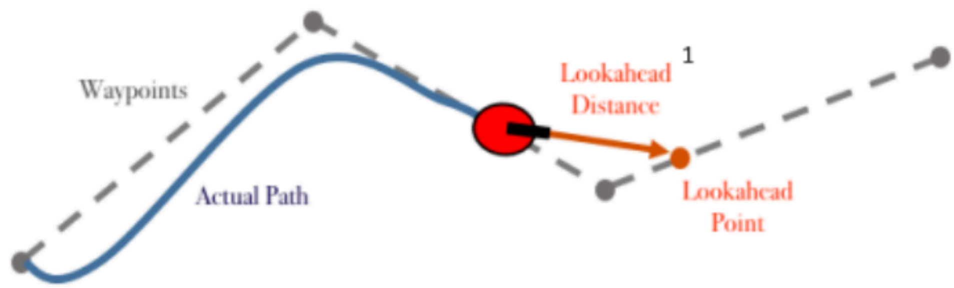


Figure 11 - Pure Pursuit Example

This is accomplished by taking a list of points (x,y), connecting them, and then choosing a "lookahead point" along the lines that the robot will attempt to follow. This will inherently cause the robot to smooth out the point map, and follow without sudden changes in direction.

The lookahead point is chosen by iterating along the path created by connecting the points and finding the furthest point that intersects a circle centered on the robot, with a set radius tuned by the programmer. Increasing this radius smooths the path, while decreasing it ensures the robot more closely follows the path.

The pure pursuit implementation in Core can either use the Autonomous Command System (ACS), or be called directly through the TankDrive class. See the sample code below for examples.

```
// Autonomous Command Controller
CommandController cmd{
   drive_sys.PurePursuitCmd(PurePursuit::Path({
       {.x=19, .y=133},
       {.x=40, .y=136},
       {.x=92, .y=136},
   }, 8), directionType::rev, .5)->withTimeout(4),
};
cmd.run();

// Standalone
while(!drive_sys.pure_pursuit(PurePursuit::Path({
           {.x=19, .y=133},
           {.x=40, .y=136},
           {.x=92, .y=136}}, 8), directionType::fwd, 0.5))
{
   vexDelay(20);
}
```

Control Loops

In order for the Autonomous Command Structure to function, we need a way to tell the robot how we want it to move. There are two broad categories of telling a robot to achieve a requested position - Feedback and Feedforward. Feedback relies on sensors and adjusts the output of the robot according to the error between where it is and where it wants to be. On the other hand, a feedforward controller takes a mathematical model of the system and creates outputs based on what it calculates to be the necessary output to achieve the goal. Additionally, there are simpler methods like Bang-Bang or Take Back Half. These adjust the outputs based on the current position relative to the target, where Take Back Half gradually refines the output until it settles at the desired position. These controller types work for many applications, but a combination of them can achieve an even better control over robot actuators.

PID

A PID controller is perhaps the most common type of Feedback control. It uses measurements of the error at its current state (proportional), measurements of how the error was in the past (integral) and measurements of how the error changes over time(derivative). The controller acts accordingly to bring the errors towards 0. We implemented a standard PID controller but made some alterations to fit our needs. The most important of these are custom error calculations. The standard error calculation function *(target - measured)* works for many of our uses but causes problems when we use a PID controller to control angles. Since angles wrap around at 360 degrees or 2π radians we wrote our own error calculation function that gives the error that accounts for this wrapping.

Feedforward

A feedforward controller differs from a feedback controller in that it does not rely on any measurement of error to command a system. Instead, built into a feedforward controller is a mathematical model of the domain. When a target is requested by the controller, the model is queried to figure out what the robot actuators must output to achieve that target. A key advantage of this form of control is that instead of waiting for an error to build up in the system, the controller acts directly to achieve the target and can reach the target much faster.

Bang-Bang

Bang-Bang control is a straightforward control methodology where the output to the system is either fully on or fully off, with no intermediate states. It's used for systems where fine control isn't necessary or possible. In this method, when the process variable is below the setpoint, the controller output is set to maximum; when above, it's set to minimum. This approach is simple and often used for systems with high inertia or where the precise control of the variable isn't critical. However, it can lead to oscillations around the setpoint and isn't suited for systems requiring precise regulation.

Take Back Half (TBH)

The Take Back Half (TBH) method is an iterative approach used to refine control in systems where overshoot is a concern. This method adjusts the output by taking back half the value of the output each time the controlled variable overshoots the target. The adjustment continues until the system settles close to the desired setpoint. TBH is particularly useful in scenarios where a fine balance between responsiveness and stability is needed, as it reduces the oscillation or overshoot often seen in simpler control methods. It's a practical choice for systems where a PID controller might be too complex or unnecessary. TBH controllers only have one tuning parameter which allows for an incredibly easy tuning experience.

Generic Feedback

Different control systems work best in different environments. Because of this, we found ourselves switching control schemes often enough that rewriting the code each time was time consuming and often led to rushed, worse quality code. To solve this problem we implemented a generic feedback interface so that none of our subsystem code needs to change when we use a different control scheme. Instead, the subsystem reports to the controller where it wants to be, measurements from its environment and some information about the system's capabilities and the controller will report back the actions needed to achieve that target. This allows for much faster prototyping as well as cleaner, less tightly coupled code.

Motion Profile

As we learn from each event, our team has evolved our approach to robot control systems, transitioning from a simple PID controller to a more sophisticated Motion Profile controller. The PID system, while fundamental, had its drawbacks, such as limited speed specification, poor response to wheel slipping, and slower reaction times. These limitations highlighted the need for a more advanced control mechanism.

Our Motion Profile controller represents a significant upgrade. It integrates precise control over position, acceleration, and velocity, allowing for optimized performance of our robot's subsystems. Unlike the PID controller, which reacts only to discrepancies between actual and desired states, our Motion Profile controller proactively manages the robot's movements. It anticipates the required actions, thereby reducing response lags. Moreover, it avoids the rigidness of a pure feedforward controller by adapting dynamically to changing conditions in competition scenarios.

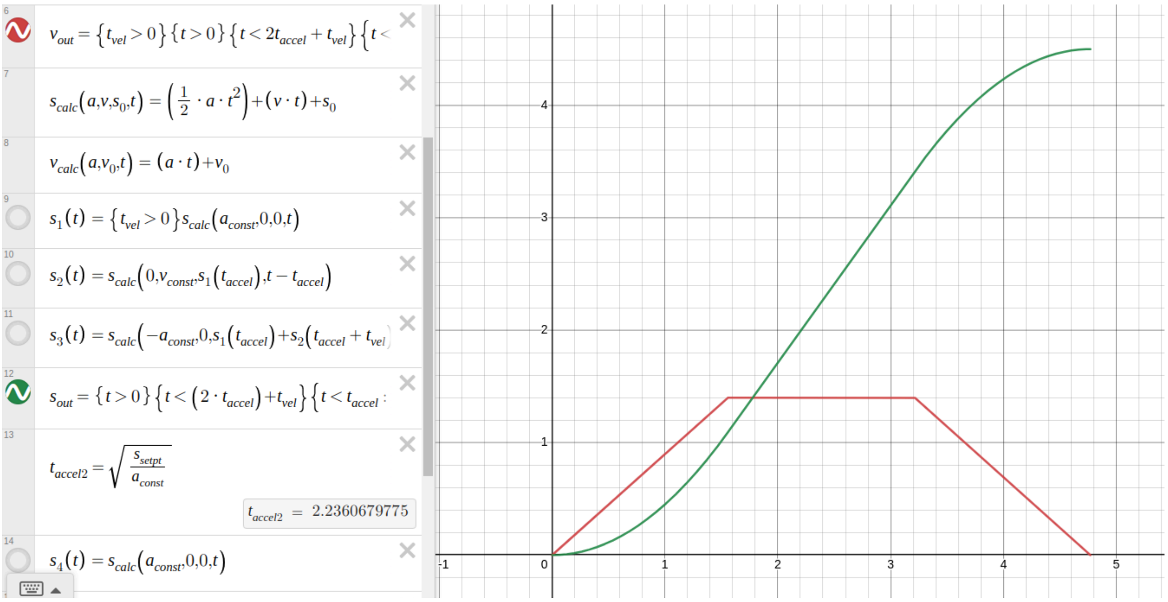


Figure 12: Trapezoidal motion profile

A key feature of the Motion Profile controller is its ability to handle varying accelerations. This functionality enables our robot to accelerate efficiently without wheel slipping, always maintaining optimal acceleration. This year, we've further refined our Motion Profile to accommodate non-zero starting and ending velocities. This enhancement allows for the seamless chaining of complex movements, ensuring smoother transitions and more fluid motion during competition tasks.

Auto Command Structure (ACS)

Principle

A recent addition to our core API was that of the Autonomous Command Structure. No more will our eyes glaze over staring at brackets as we trawl through an ocean of anonymous functions nor lose our way in a labyrinthine state machine constructed not of brick and stone but blocks of ifs and whiles. Instead, we provide named Commands for all the actions that our robot can execute and infrastructure to run them sequentially or concurrently. The API is written in a declarative way allowing even programmers unfamiliar with the code to see a step-by-step, annotated guide to our autonomous path while keeping the procedures of how to execute the actions from hurting the readability of the path.

```
CommandController auto_non_loader_side(){
    int non_loader_side_full_court_shot_rpm = 3000;
    CommandController non_loader_side_auto;

    non_loader_side_auto.add(new SpinRPMCommand(flywheel_sys, non_loader_side_full_court_shot_rpm));
    non_loader_side_auto.add(new WaitUntilUpToSpeedCommand(flywheel_sys, 10));
    non_loader_side_auto.add(new ShootCommand(intake, 2));
    non_loader_side_auto.add(new FlywheelStopCommand(flywheel_sys));
    non_loader_side_auto.add(new TurnDegreesCommand(drive_sys, turn_fast_mprofile, -60, 1));
    non_loader_side_auto.add(new DriveForwardCommand(drive_sys, drive_fast_mprofile, 20, fwd, 1));
    non_loader_side_auto.add(new TurnDegreesCommand(drive_sys, turn_fast_mprofile, -90, 1));
    non_loader_side_auto.add(new DriveForwardCommand(drive_sys, drive_fast_mprofile, 2, fwd, 1));
    non_loader_side_auto.add(new SpinRollerCommand(roller));

    return non_loader_side_auto;
}
```

Figure 13: ACS code from the 2023 competition season

Updates

This season, we found ourselves annoyed with having to repeat basic things such as `path.add(...)` and having to write `new ThingCommand(...)` over and over again. Our first solution to this was “shortcuts”. These were member functions of subsystems that would allocate, initialize and return an auto command for that subsystem. So, instead of `path.add(new DriveForwardCommand(drive_sys, drive_fast_mprofile, 20, fwd)` we could simply write `path.add(drive_sys.DriveForwardCommand(20, fwd)).`This reduced a great deal of typing but still left us with some issues.

The most hazardous, rather than the simply annoying downside of last year's system, was the memory unsafety of this system. Since our auto commands must use virtual functions, they must be on the other end of a pointer. So, they must be allocated using new or they must be initialized statically before we write the path which is a terrible user experience (Though, if constrained by an embedded system where allocating on the heap was deemed dangerous, the system could work with this). This became a real issue when we began to write more complicated constructs such as branching, asynchronous, and repeated commands as it became dangerously unclear who was responsible for deallocating these objects. As a solution for this, we developed an RAII wrapper for the Auto Command Interface. Inspired by C++’s `std::unique_ptr`, this wrapper provides a memory safe, value based way of using auto commands while still maintaining their adaptability. We used C++’s ideas of move semantics and ‘Resource Allocation Is Initialization’ to practically solve memory management so programmers (and even non programmers) can focus on writing paths.

```
CommandController cmd{
    odom.SetPositionCmd({.x = 16.0, .y = 16.0, .rot = 225}),
    // 1 - Turn and shoot preload
    {
        cata_sys.Fire(),
        drive_sys.DriveForwardCmd(dist, REV),
        DelayCommand(300),
        cata_sys.StopFiring(),
        cata_sys.IntakeFully(),
    },
    // 2 - Turn to matchload zone & begin matchloading
    drive_sys.DriveForwardCmd(dist + 2, FWD,0.5)
        .with_timeout(1.5),

   // Matchloading phase
   Repeat{
       odom.SetPositionCmd({.x = 16.0, .y = 16.0, .rot = 225}),
       intakeToCata.with_timeout(1.75),
       cata_sys.Fire(),
       drive_sys.DriveForwardCmd(10, REV, 0.5),
       cata_sys.StopFiring(),
       cata_sys.IntakeFully(),
       drive_sys.TurnToHeadingCmd(load_angle, 0.5),
       drive_sys.DriveForwardCmd(12, FWD, 0.2).with_timeout(1.7),
   }.until(TimeSinceStartExceeds(30))
};
```

Figure 13: ACS code going into the 2024 competition season

Now that we were free to use auto commands without fear for leaking memory or messing with currently running commands, we began to create more powerful constructs such as branching on runtime information, timeouts so the robot can decide what to do based on how much time is left in the auto or skills period, fearless concurrency (driving and reloading at the same time), and a much much nicer user interface. This declarative, safe, and straightforward method of writing auto paths lets us spend less time writing and debugging custom code and more time exploring and optimizing auto paths.

Serializer

One pain point we found last year was configuring auto paths, color targets, path timeouts, and other parameters that changed often but for the most part should be persistent. Commonly, we found ourselves redeploying code at the last minute before a match. To solve this, we wrote a class that takes control of a file on the SD card to which users can read and write values at runtime using a simple key-value interface. This keeps us from having to change a value, redeploy, repeat which cost us valuable time in the past.

Screen Subsystem

Principle

One of the most powerful elements of the V5 Brain is the fairly substantial touch screen. However, its simple drawing API limits its utility as one person's part of the code will draw over another since there is no larger abstraction controlling who draws when. We have many different subsystems on our robot to observe and debug and many parameters that can be tuned at run time and the screen provides a way to do this. We provide an API that provides a 'page' interface that can be inserted into a slideshow-like interface. Each 'page' provides two functions, an update and a draw. The update runs more frequently allowing touch input and data collection at a reasonably fast rate while the draw function runs less frequently to not cause too much overhead on the system. At startup, users provide the screen subsystem a list of pages and the screen subsystem handles orchestration and input in a background thread while other robot code runs unaffected.

```
pages = {
    new AutoChooser({"Auto 1", "Auto 2", "Auto 3", "Auto 4"}),
    new screen::StatsPage(motor_names),
    new screen::OdometryPage(odom, 12, 12, true),
    cata_sys.Page(),
};

screen::start_screen(Brain.Screen, pages);
```

Figure 14: Configuration for the screen subsystem

Pages

Odometry Page

The odometry page has proved incredibly useful in writing and debugging auto and auto skills paths. It shows a picture of the robot on the field as well as a print out of the actual x,y coordinates and heading of the robot. Since we write our autos with respect to the coordinate system of the field, having a map to look at makes development much simpler.

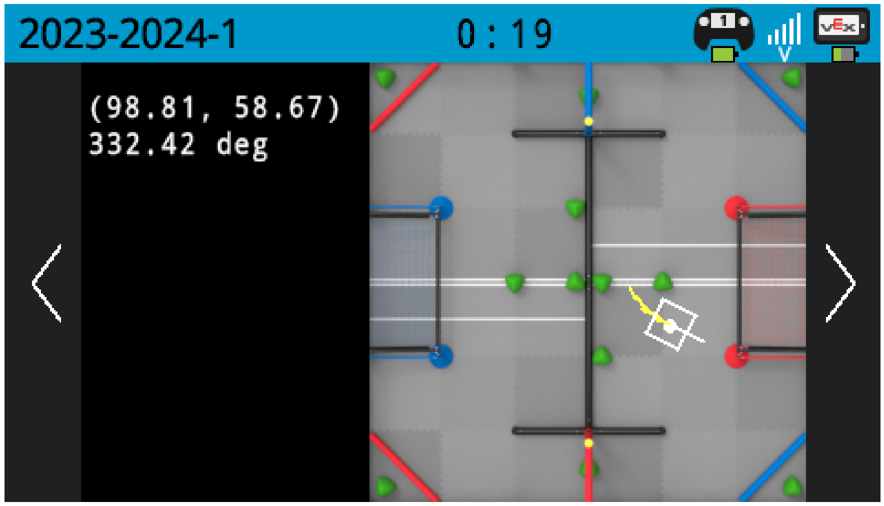


Figure 15: A field display for the Over Under season

PID Tuner

PID controllers are integral to many subsystems on our robots. Our drive code uses them for turning and forward motion, our catapult uses them for reloading, and subsystems across seasons require them for precise control. Tuning them, however, can be incredibly tedious. Changing one value, redeploying, and repeating over and over again is time consuming and unnecessary. Since we have a wonderful touchscreen, we simply added a series of sliders for PID parameters and we can now easily adjust a PID tuning in seconds rather than minutes saving a great deal of time on an already time consuming part of robot development.

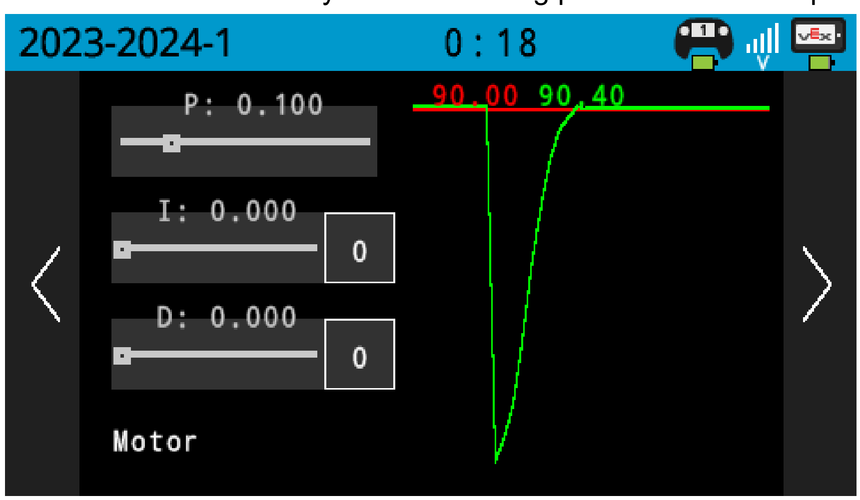


Figure 16: Tuning a motor for reaching an angle

Motor Stats

One would think it an easy step to remember to plug motors in, and yet multiple times this season we have been bewildered and hindered by an unplugged motor. This page was written to continuously display that the motor had been unplugged and was not cancellable like the built-in VEX alert. This screen also displays what port to plug it into as well as a color coded temperature displaying when the robot needs to cool down. This tool proved extremely useful as we discovered an alarmingly high number of dead or nonfunctioning ports on the brain.

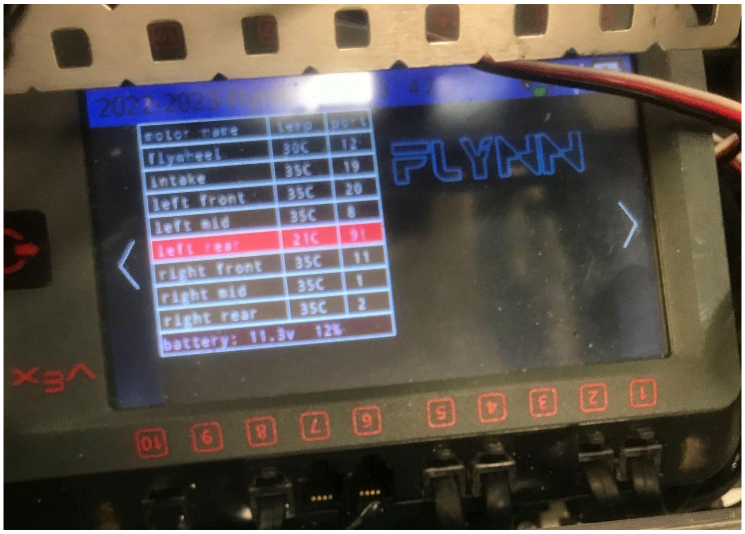


Figure 17: Motor Stats screen from our 2023 robot

Cata System Page

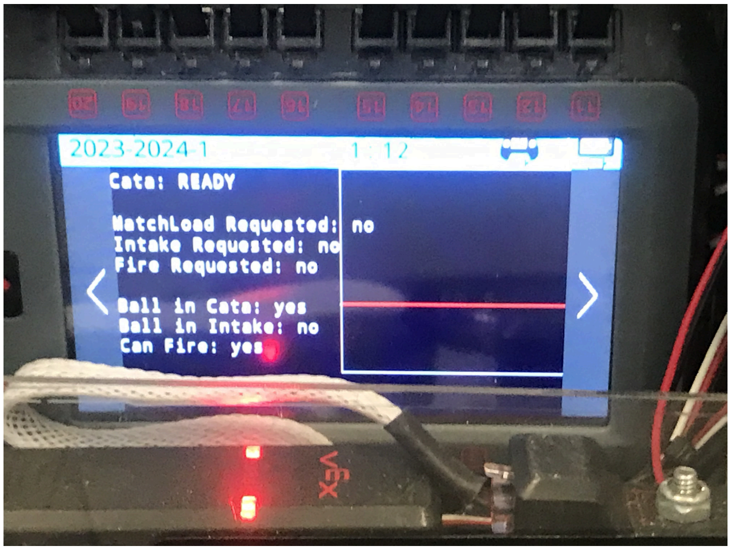


Figure 18: The catapult status page. Includes a graph of Catapult PID values.

Catapult System

Motivation

Vex’s Over Under game requires the effective utilization of the fascinatingly shaped triball. After much deliberation, our team decided on a catapult to launch the game element across the field and a reversible intake for picking up and scoring the triball. This system gives us a great deal of flexibility and power for strategy but does increase the system's complexity. This complexity mostly stems from the orchestration of intaking with catapult reloading such that we do not jam our catapult and never intake multiple game pieces leading to a disqualification.

Initial Design

We implemented a state machine that receives inputs from the controller, a distance sensor in the intake, a distance sensor in the catapult, and a potentiometer for watching the catapult’s position. The system runs the appropriate motors to either intake to hold the triball, reset the catapult, intake into the catapult, or shoot depending on its state. Because we have so many sensors, we can determine when intaking would lead to disqualification and simply not honor the intaking command.

These messages are a simple enum that one passes to `CataSys::send_command()`. This was originally intended to make writing multi-threaded code less error-prone as there was one thread-safe and simple way to interact with the subsystem, rather than many disparate methods some of which are meant for internal usage of the class on the running thread and some accessors and setters meant to used from the user thread. Although it started for implementation ease, it naturally brought about a very simple interface for auto. Instead of sending a command on a button press, we simply send a command at a certain point in our auto path and the system reacts accordingly.

Successor

Though the idea of the state machine modeled the intake and catapult system well, our haphazard implementation (very large and complicated switch statement on a worker thread) made changes exceedingly difficult. As we began competing, we identified changes we wished we could make to make driver and autonomous control easier and handle unforeseen hardware faults. However, our system was hard to read, modify, and all but impossible to prove correct.

Inspired by TinyFSM and other off the shelf C++ libraries for this problem, we created a generic state machine class that handles state transitions, background thread execution, and observability. While this tradeoff led to more code overall, it’s explicitness and separation of concerns allowed members to make changes in the behavior of the system without fear of deadlocking the threads or unknowingly modifying other states. The generic StateMachine class will remain in our Core library and can be reused year to year to achieve these benefits for any other stateful subsystem.

```cpp
struct Reloading : public CataOnlySys::State {
    void entry(CataOnlySys &sys) override {

        sys.pid.update(sys.pot.angle(vex::deg));
        sys.pid.set_target(cata_target_charge);
    }

    CataOnlySys::MaybeMessage work(CataOnlySys &sys) override {
        // work on motor
        double cata_deg = sys.pot.angle(vex::deg);
        if (cata_deg == 0.0) {
            // adc hasnt warmed up yet, we're getting zero results
            return {};
        }
        sys.pid.update(cata_deg);
        sys.mot.spin(vex::fwd, sys.pid.get(), vex::volt);

        // are we there yettt
        if (sys.pid.is_on_target()) {
            return CataOnlyMessage::DoneReloading;
        }
        // otherwise keep chugging
        return {};
    }

    CataOnlyState id() const override { return CataOnlyState::Reloading; }
    State *respond(CataOnlySys &sys, CataOnlyMessage m) override;
};
```

Explicit separation of states allows simpler, more readable code

Due to the message passing interface to the catapult and intake system, this change was able to be made with very few modifications to the external interface of the system meaning driver code and autonomous paths did not have to be rewritten to use the advantages of the new system - a saving grace as we made this modification in the middle of competition season.

Vision

With the unpredictable way triballs roll across the field, our robots need a way to repeatably track the game objects during the autonomous period. And so, a vision sensor is placed inside the intake subsystem on the front of the robot.

The Vex Vision sensor is notorious among teams for being unreliable, being highly dependent on field lighting conditions and often sensing random objects, sending the robot off course. Our team explored different methods of filtering and lighting to combat these issues, and are now successfully tracking triballs in our autonomous programs.

Filtering Vision Objects

The first issue to address was filtering - making sure the robot tracks the correct objects. Currently, we run a filtering algorithm that removes all vision objects that don't follow a strict criteria:

- Minimum area (object width * height)
- Maximum area
- Minimum aspect ratio (object width / height)
- Maximum aspect ratio
- Min / Max X value
- Min / Max Y value

Finally, the filtered objects array is sorted by area, so that the largest objects are easily accessible at the start of the array. Here's an example of how it's used:

```
vision_filter_s filter{
   .min_area = 2000,
   .max_area = 100000,
   .aspect_low = 0.5,
   .aspect_high = 2,
   .min_x = 0,
   .max_x = 320,
   .min_y = 0,
   .max_y = 240,
};
vector<vision::object> obj_list = vision_run_filter(filter);
```

Standardizing Lighting

In past competitions, we've found differing lighting conditions can spell an unfortunate end for autonomous programs using vision. Spotlights, windows and even the color temperature of the overhead lights caused slight differences which would cause the color profile to be off. We were able to completely eliminate this by adding a custom light to the robot - a board that uses two high-powered LEDs switched with a MOSFET over the three wire ports. Here's the schematic:

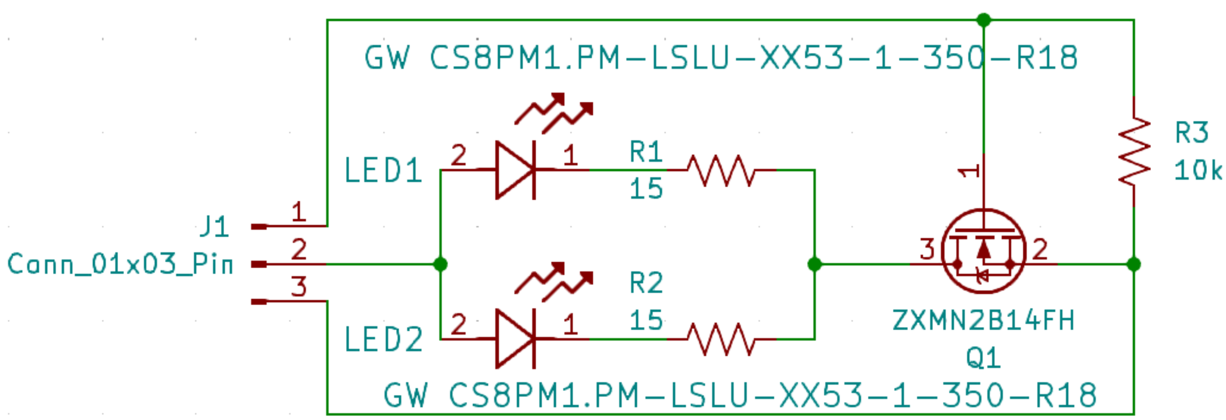


Figure 19 - LED Board schematic

The low-side FET switches power via the signal pin, allowing the programmer to use PWM to dim the lights as needed.

Here's the final PCB built for competition:

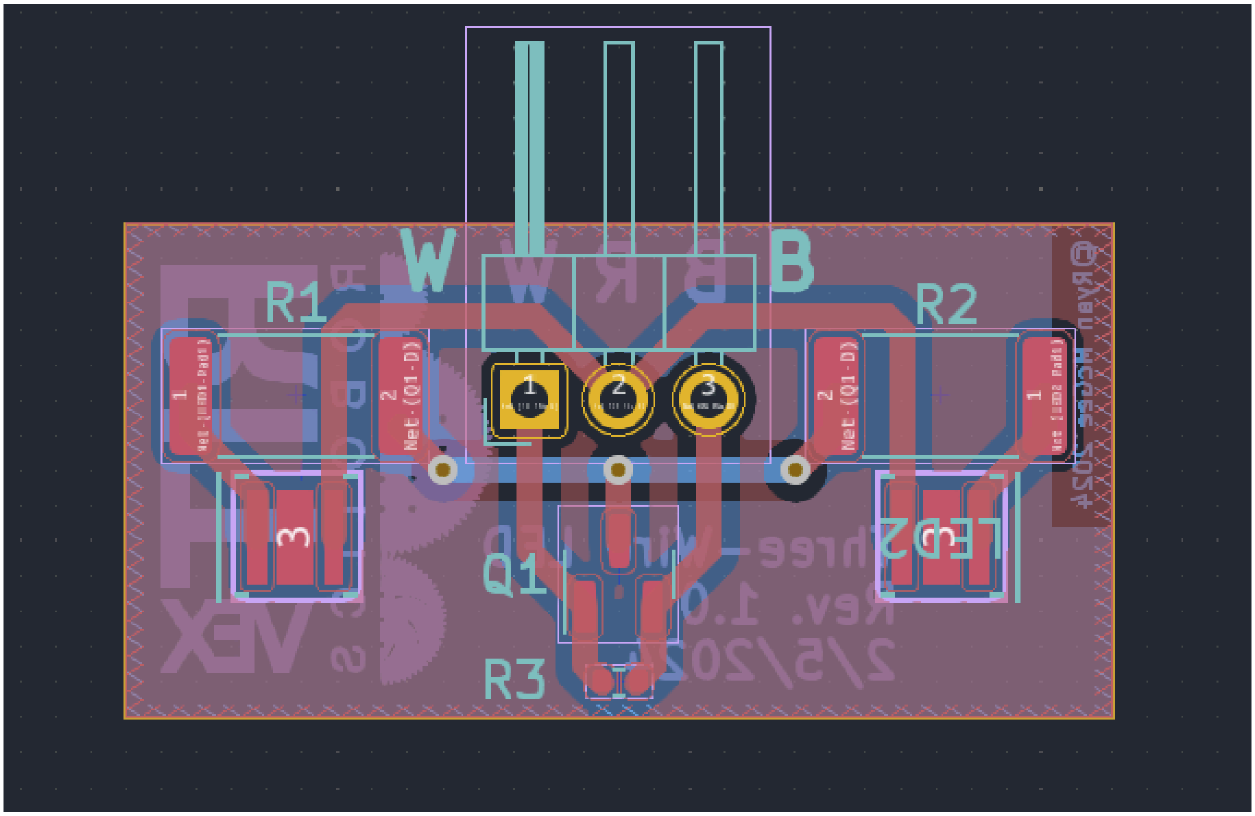
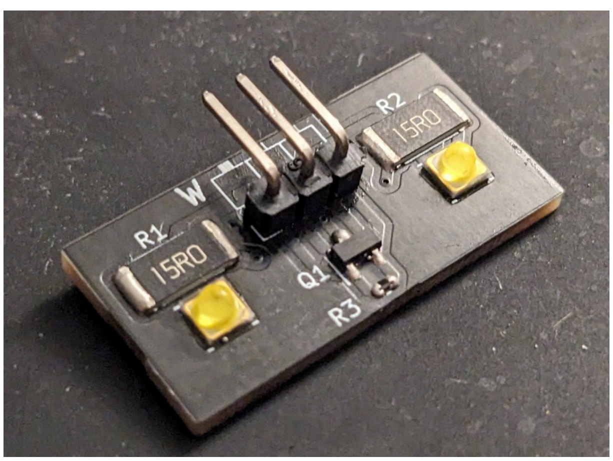


Figure 20 - LED Board PCB design



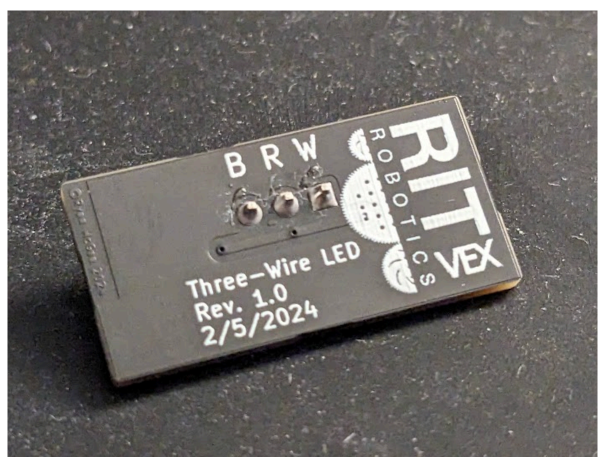


Figure 21 - LED Board, Front

Figure 22 - LED Board, Back

The lighting system was tested and successfully used at the West Virginia tournament, where the robot was able to score five triballs in one autonomous program using this vision system.

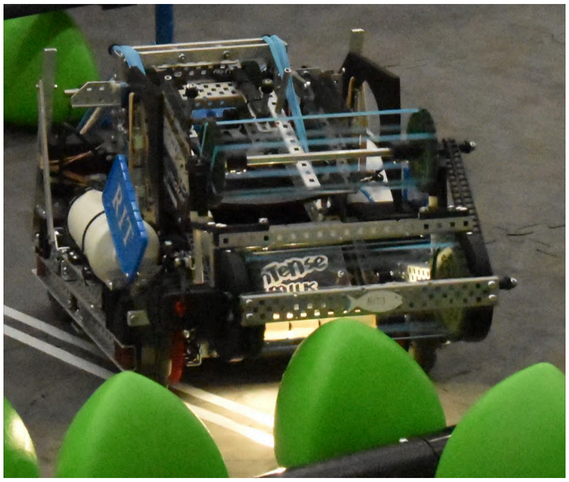


Figure 23 - Vision Tracking in Auto

Figure 24 - LED board at full power (~2 Watts)

Core: Ongoing Projects

Rust

Over the course of the year, we have experimented with rewriting our Core API in Rust, a multi-paradigm programming language focused on performance and safety. Rust offers several potential advantages over C++:

Motivation

Memory Safety

One of the primary benefits of Rust is its emphasis on memory safety without sacrificing performance. Rust's ownership model ensures that memory is managed correctly at compile time, reducing the risk of memory leaks and buffer overflows which are common issues in C++. This is especially crucial in robotics, where memory management errors can lead to system crashes or unpredictable behavior in real-time operations.

Concurrency

Rust's approach to concurrency is another major advantage. Concurrency errors, like race conditions, are hard to debug and can be catastrophic in robotics, leading to inconsistent states and erratic behavior. Rust's type system and ownership model prevent data races at compile time, making concurrent programming more reliable and easier to reason about.

Performance

In terms of performance, Rust is comparable to C++, which is essential in robotics where processing speed and response time are critical. Rust's zero-cost abstractions mean that high-level constructs do not add overhead at runtime. This allows developers to write high-level code without compromising on performance, an important consideration in robotics where every millisecond can count.

Improved Code Maintenance and Readability

Rust also offers improved code maintainability and readability. Its modern syntax and language features make it easier to write clear and concise code. This reduces the cognitive load on developers, making it easier to develop and maintain complex robotic systems. The compiler's strictness also ensures that many potential bugs are caught early in the development cycle, reducing the time spent on debugging.

Growing Ecosystem and Community

The Rust ecosystem is rapidly growing, with a strong focus on safety and performance. There are increasing numbers of libraries and tools being developed for Rust, including those specifically for robotics. The Rust community is known for its dedication to improving code quality and security, which aligns well with the needs of robotics development.

Overall

While the transition from C++ to Rust in a robotics context requires investment in terms of learning and codebase modification, the benefits in memory safety, concurrency handling, performance, and maintainability make it a compelling choice. The modern features of Rust, combined with its growing ecosystem and community support, position it well for developing robust, efficient, and safe robotic systems.

Progress

Though progress slowed as competition season began, our rust build system is moving out of the proof of concept stage and into something useful. We setup a `cargo` (rust's build system manager) target and can `cargo build` a vex project into an architecture-correct .elf file linked according to vexcode's standard library version and linker configurations. We then created a simple python script to convert the .elf file into the stripped binary file that the vex brain expects and call the `vexcom` tool provided by the vscode extension to send binaries to the brain.

Findings

Though we did not have much time before our small software team's resources were needed elsewhere, our experiments with Rust programming for VEX found many interesting things.

A surprise we came across is that for proper and safe rust environments one must provide a panic handler. This will be called whenever an error occurs or the programmer signals that the specified behavior is invalid. Though rust does many things to insure 'if it compiles correctly it runs correctly' there is still behavior that should be signaled to be an error at run time. With the custom panic handler we are able to provide detailed error messages including line numbers and function names - a feature that is sorely missed when programming with the C/C++ API.

Though Rust does come with many benefits, we did find a blocker that is limiting more widespread adoption on the team. The C/C++ API dynamically links the C and C++ standard library after deploying such that a much smaller binary must be transferred to the brain, a life saver when wirelessly uploading. Even with aggressive minimal size optimizations, the requirement to statically link rust core library functions means even simple rust binaries would match the size of our largest C/C++ projects. The PROS ecosystem ran into a similar problem and did work with hot/cold linking in order to not deploy non-changing code each time and we are looking to explore a similar solution. However, most of our research is into undocumented areas of the VEX ecosystem and this feature is still in the early phase of development.

The work on the rust port was split between two members: one of whom ported the API of core and modified it to fit into the rust programming style and safety model and one who set up the compiler toolchain and low level system for interfacing with the vex C/C++ library. Though this was originally an organizational decision, we realized that much of core could be completely abstracted away from dealing with VEX specific components and could operate on hardware that fulfills specific interface requirements. For example, as long as we can send a voltage to a motor and read a position our drivetrain and flywheel subsystems would work no matter the actual hardware. Thanks to rust's powerful generic programming features, this flexibility can be used without sacrificing helpful compiler errors (a common C++ issue) and without sacrificing performance using runtime polymorphism.

N-Pod Odometry

Motivation

Although we have been working on the GPS odometry system, wheel odometry is still vital. It provides great small-scale, quickly updating positions as well as having near-perfect, continuous, local velocity which a GPS system can not achieve. We use odometry in two ways; either tank or differential odometry where there is one wheel on either side of the drivetrain alongside the drive wheels and 3-wheel odometry where we have 3 wheels at ninety degrees to each other. Tank odometry is limited as it can not track horizontal movement and we simply hope that we never move sideways, though it is easiest to implement in the robot so it is our most commonly used system. 3-wheel odometry solves the side-to-side problem but is much harder to implement in hardware owing to the extra wheel where other subsystems would need space.

In a plea for mercy from the hardware team, we agreed that we would take tracking wheels wherever and we could make do. Though we once again got stuck with a tank system, if our dream of more tracking wheels ever comes true we would need code to handle such a system. Also, since tank and 3 wheel odometry are special cases of an n-pod system, we could reduce code duplication.

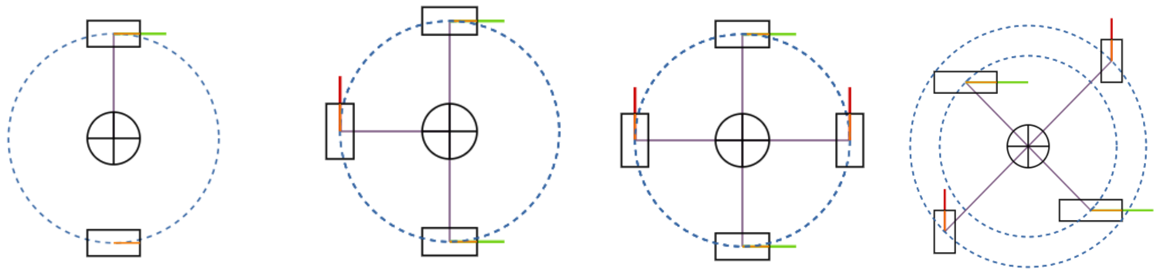


Figure 25: 2 pod, 3 pod, and arbitrary pods such a system could handle.

Syntax

After much brainstorming and many mad scientist whiteboard drawings, we believe that we have the fundamentals of a system figured out. Unfortunately, other responsibilities to the team came up so we do not yet have a functioning implementation of the system.

Imagine a robot with *n* number of tracking omni wheels. We could read encoder values E_1, E_2, ..., E_3 from the system in radians from the initial position. As well, each encoder has a configuration $(x_1, y_1, \theta_1, r_1)$, ..., $(x_n, y_n, \theta_n, r_1)$ describing its position (*x, y*) relative to the center of rotation, an angle describing its orientation relative to the robot frame (θ), and a radius of the wheel (*r*).

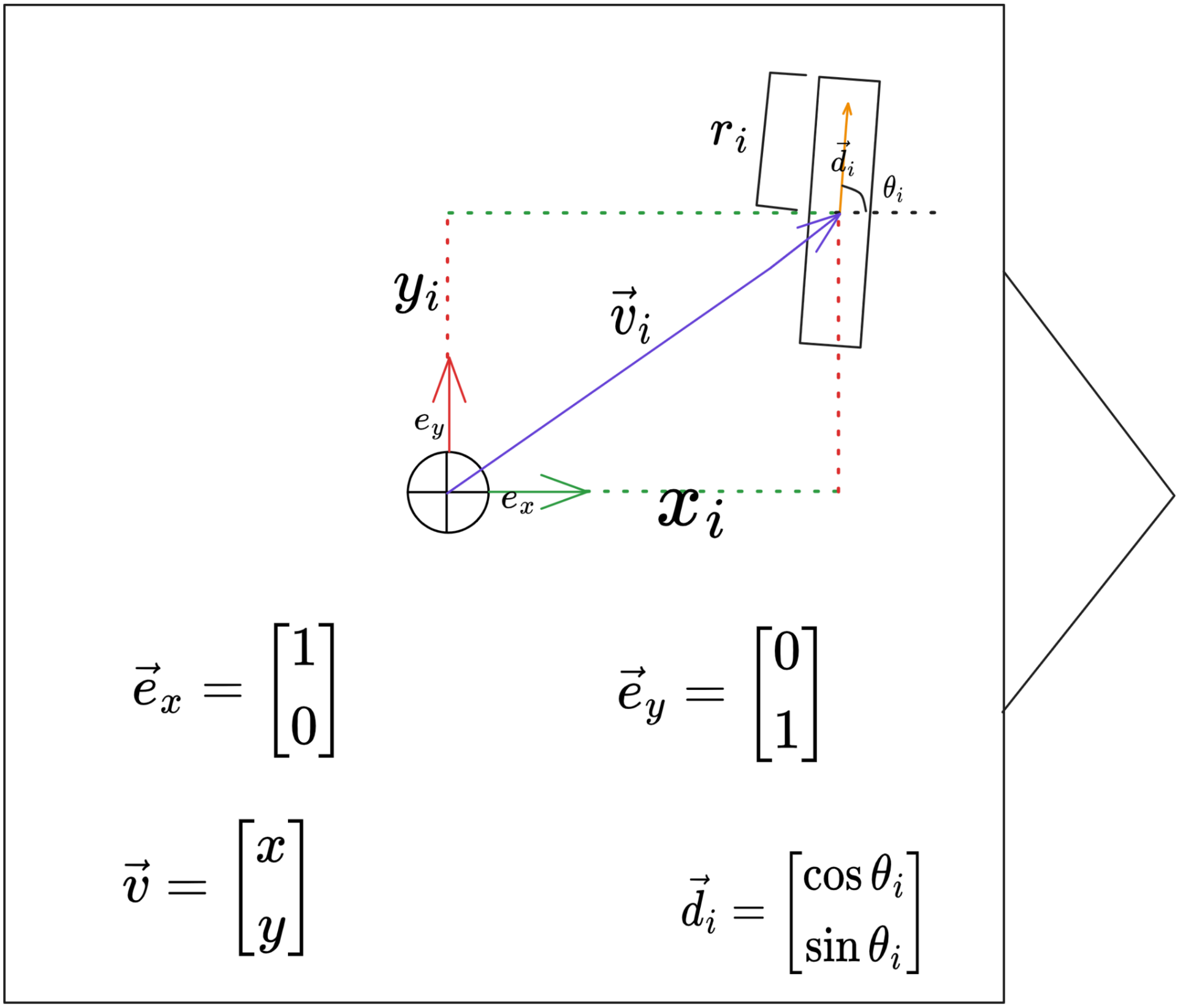


Figure 26: The configuration of a tracking wheel on the robot. (e_x, e_y) are the basis vectors of our coordinate system - the X and Y axes of the robot coordinate frame. d_i is the direction vector of the tracking wheel.

Now, if we pretend that these wheels are powered and we wish to translate and rotate the robot according to some controller input $(x,\ y,\ \theta)$ we can develop a formula for how much each wheel needs to rotate to move the robot in that direction with that rotation. Luckily, since the tracking wheels are omni wheels that roll freely in the axis against their "forward" direction, we do not need to worry about dragging a wheel so long as it is spinning the correct amount in its "forward" direction. For a desired $(x,\ y,\ \theta)$ (in the robots reference frame), for the *i*-th encoder, we say $E_i = xF_{xi}$. That is, for a movement in the x-axis the rotations of the *i*-th encoder, are the desired x movement times some scalar factor (*F)* for how far this specific wheel would rotate. Similarly, for a *y* only and θ only movement, $E_i = yF_{yi}$ and $E_i = \theta F_{\theta i}$ respectively.

Deriving Factors

F_x

F_x depends on the direction vector $\vec{d}$ of the omni-wheel. If the omni-wheel is facing along the x-axis, F_x will be higher whereas if the omni-wheel is directly perpendicular to the x-axis, it will not spin when you move only in the x-direction. Since $\vec{e}_x$ and $\vec{d}$ are unit vectors, how closely they are related is given by $\vec{e}_x \cdot \vec{d} = \cos(angle\ between\ x\ axis\ and\ wheel)$

F_x also depends on the radius of the wheel *r*. One full rotation of the wheel moves a distance of $C = 2\pi r$. If we drive in the direction of the wheel *i* inches, the wheel will complete $\frac{i}{2\pi r}$ revolutions. If we measure the rotations in radians, the wheel will travel $\frac{i}{r}$ radians. That is, if the encoder wheel travels *E* radians, we will have traveled *Er* inches in that direction.

So, the distance traveled in the x direction of a wheel pointing in the direction $\vec{d}$, rotating *E* radians is $x = Er(\vec{e}_x \cdot \vec{d})$. This gives since F_x as how many inches per radian turned,

$$F_x = \frac{x}{E} = r(\vec{e}_x \cdot \vec{d})$$

F_y

F_y is derived almost identically as F_x just instead of testing against $\vec{e}_x$ we test against $\vec{e}_y$. So,

$$F_y = \frac{y}{E} = r(\vec{e}_y \cdot \vec{d})$$

F_θ

F_θ is a little more complicated since it is determined by the position of the wheel $\vec{v}$ as well as the orientation of the wheel $\vec{v}$

Imagine that the robot turns an angle of θ_r measured in radians. A wheel that is perfectly perpendicular to the rotation will travel an arc with distance $S = ||\vec{v}||\,\theta_r$ by the arc length formula where the 'radius' of the arc is defined by the length of the vector $\vec{v}$.

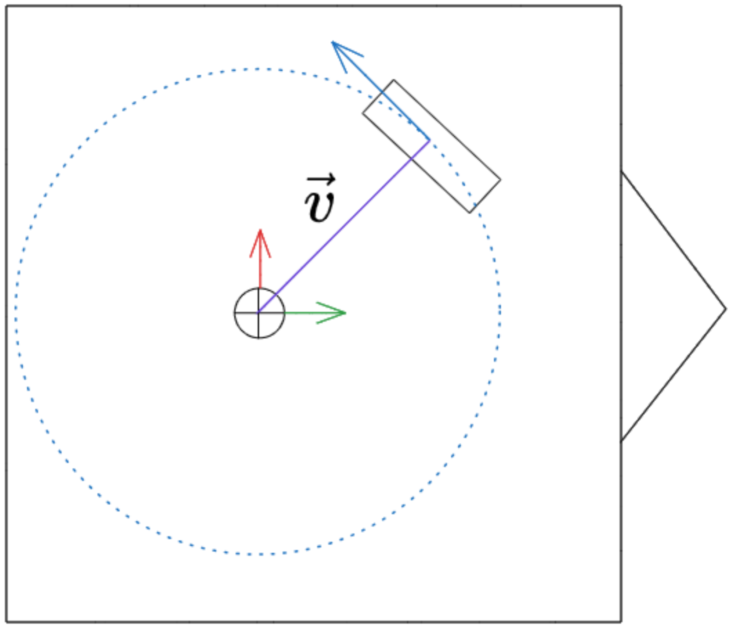
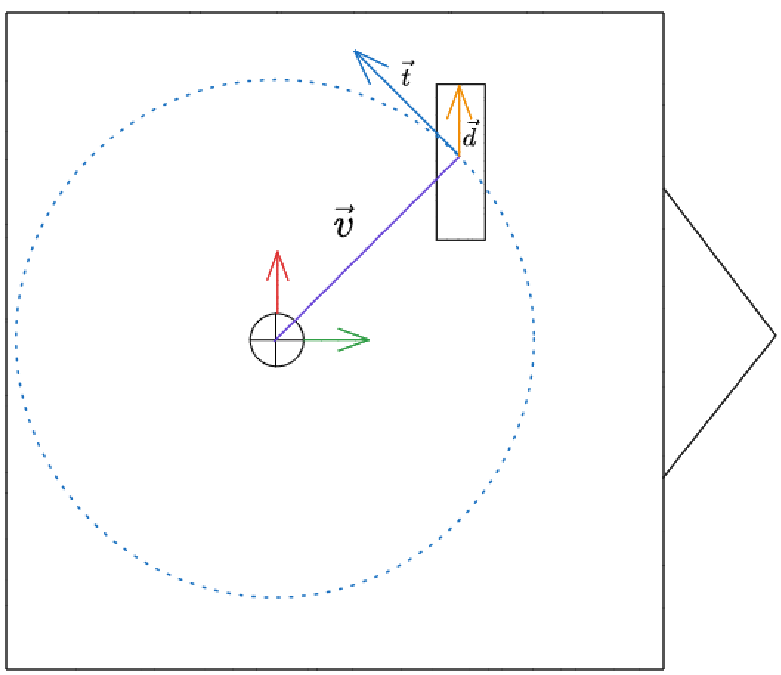


Figure 27: A conceptual perfectly perpendicular wheel

So, if we have a wheel that is always tangent to the rotation, it will travel

$$E_t r = S = ||\vec{v}||\theta_r$$

Since our wheel isn't guaranteed to be perfectly tangent to the arc, we have to use our dot product trick to get the component of its motion that is tangent to the turning circle. That is, instead of comparing to $\vec{e}_x$ or $\vec{e}_y$ we compare to the normalized vector $\vec{t}$ tangent to the turning circle.



$$E_t r = Er(\vec{t} \cdot \vec{d})$$

So

$$Er(\vec{t} \cdot \vec{d}) = S = ||\vec{v}||\theta_t$$

Since $\vec{t}$ is just a unit vector 90 degrees counterclockwise of $\vec{v}$, We can find it by multiplying $\vec{v}$ by the rotation matrix for 90 degrees and normalizing giving

$$\vec{t} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} norm(\vec{v}) = \begin{bmatrix} -norm(\vec{v}).y \\ norm(\vec{v}).x \end{bmatrix}$$

So

$$F_\theta = \frac{\theta_r}{E} = \frac{r(\vec{t} \cdot \vec{d})}{||\vec{v}||} = \frac{r(\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} norm(\vec{v}) \cdot \vec{d})}{||\vec{v}||} = \frac{r(\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \vec{v} \cdot \vec{d})}{||\vec{v}||^2}$$

Why factors

These factors make solving this problem much simpler. For the forward case, for some wheel *i*, its rotation is the sum of all the motions applied to it. So $E_i = F_{xi}x + F_{yi}y + F_{\theta i}\theta$. So, for all the wheels, we plug in the commanded (x, y, θ) to each wheel's factors to get its necessary rotation. Since the factors depend only on the wheel’s pose in the frame, these can be calculated once at the start of the program and are constant (unless the frame breaks apart, in which case the robot has other problems).

Now Do It Backwards

We have now solved the forward system for when we have a delta of our pose and want our wheel deltas. Now we must take our wheel deltas and solve for our pose delta. We have our formulas for each wheel's encoder motion and can consider this as a system of linear equations. At runtime, we have our wheel encoder deltas we can plug in and then we can solve the system of linear equations. This requires that we have enough data to satisfy the equations. That is, we need at least 3 separate wheels with at least some angle between them, or else the system will be not fully constrained. In the case of tank odometry, we only have two wheels but as outside observers we know we can not measure change in one dimension. So, we know one variable is zero and then have two remaining free variables and two equations to satisfy the system. For robots with greater than three encoders, we have an over-constrained system of equations but this is not an issue. Since all the encoders are modeled on a physical system, they should agree on what the solution is. Using the technique of least squares regression, we can find our (x, y, θ) to solve the over-constrained system that minimizes the error between equations. This also gives us a way to detect errors in our drive train. If a wheel gets jammed, its encoder reading will disagree with the rest of the system, and the error value will measurably increase. If we monitor this error value we can diagnose mechanical or electrical issues from the code.

$$T = \begin{bmatrix} F_{x1} & F_{y1} & F_{\theta 1} \\ \vdots & \vdots & \vdots \\ F_{xn} & F_{yn} & F_{\theta n} \end{bmatrix}$$

$$\begin{bmatrix} \frac{\text{Length}}{\text{Angle}} & \frac{\text{Length}}{\text{Angle}} & \frac{\text{Angle}}{\text{Angle}} \\ \vdots & \vdots & \vdots \end{bmatrix}$$

transfer matrix
from robot velocity
to encoder velocities
(f for factor)

$$\vec{X} = \begin{bmatrix} \frac{dx_{robot}}{dt} \\ \frac{dy_{robot}}{dt} \\ \frac{d\theta_{robot}}{dt} \end{bmatrix}$$

$$\begin{bmatrix} \frac{\text{Distance}}{\text{Time}} \\ \frac{\text{Distance}}{\text{Time}} \\ \frac{\text{Angle}}{\text{Time}} \end{bmatrix}$$

pose velocity

$$\vec{E} = \begin{bmatrix} E_1 \\ \vdots \\ E_n \end{bmatrix}$$

$$\begin{bmatrix} \frac{\text{Angle}}{\text{Time}} \\ \vdots \\ \frac{\text{Angle}}{\text{Time}} \end{bmatrix}$$

encoder wheel
velocities

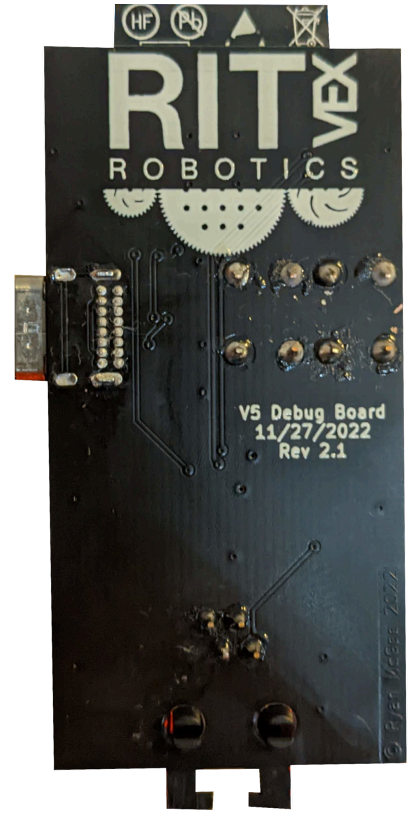
$$T\vec{X} = \vec{E}$$
$$\vec{X} = T^{-1}\vec{E}$$

or in the case where the matrix is not invertible, find the best solution

The linear algebra behind the solution

V5 Debug Board

The large number of features added to core, while extremely useful, are also very difficult to debug. Without a proper real-time c++ debugger and one stream serial data for print statements, data parsing can get very messy. The improvements to the Screen subsystem have helped, but a remote solution is needed to avoid chasing after the robot to get visual data.



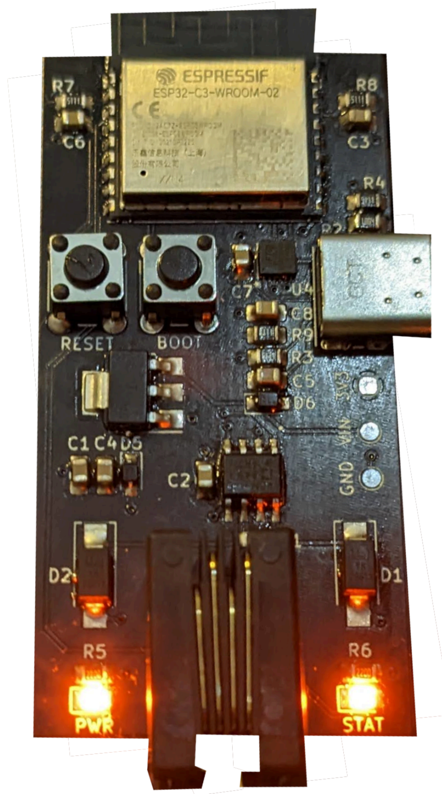


Figure 28 - Debug Board (Back)

Figure 29 - Debug Board (Front)

The V5 Debug Board is a custom PCB designed by our team specifically to interface with the V5 Smart Ports, host a ROS2 node and a WiFi access point for programmers to connect to with laptops. This board is designed to ingest any kind of data and use it for graphs, real-time tuning and even displaying a 3D model of the robot on a virtual field using odometry data. This data can be viewed using either ROS' RViz or Foxglove visualization software.

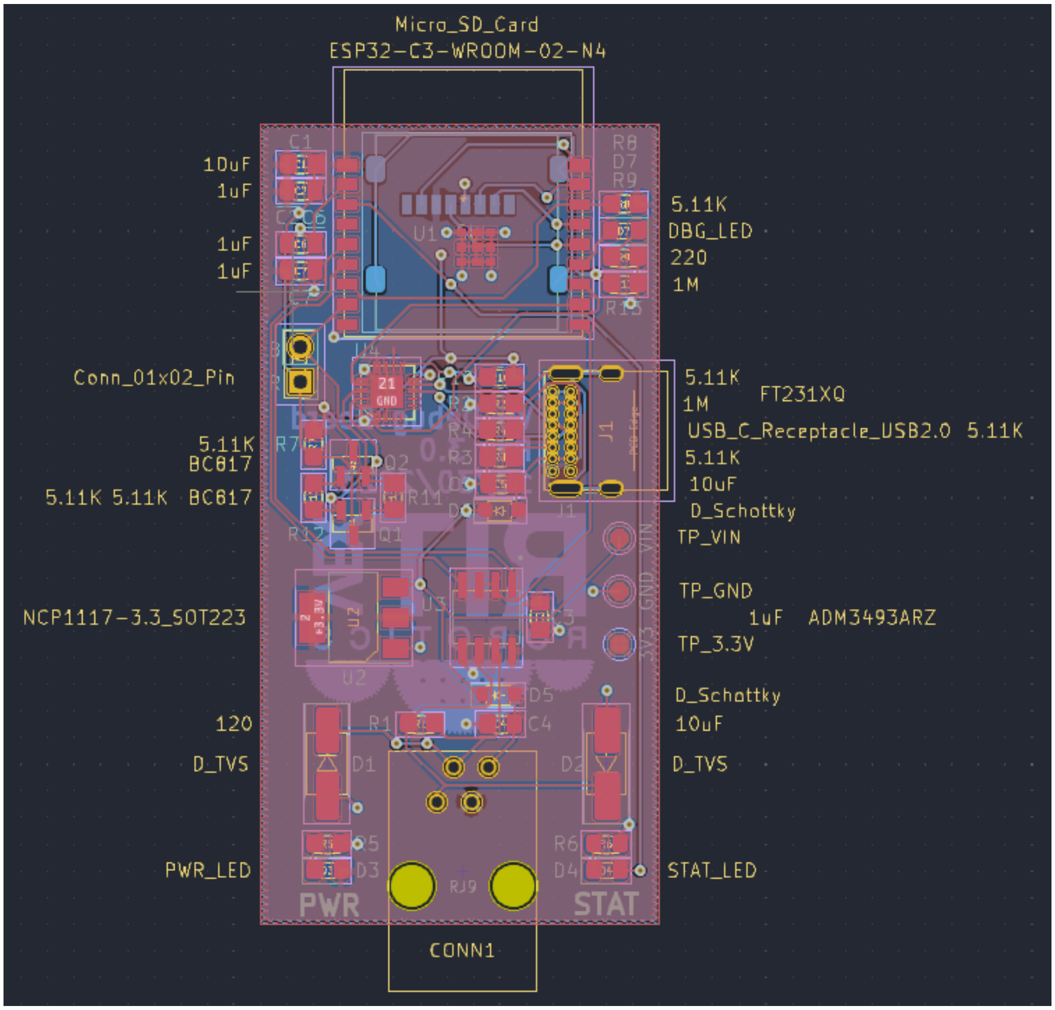


Figure 30 - Debug Board PCB Layout

Hardware design is nearing completion, with 3 revisions built and tested. Revision 3.0 is powered by an ESP32-C3-WROOM2 microcontroller, and uses an RS-485 transceiver to communicate with the Brain over a smart-port. The new addition of a Micro-SD card allows users to upload their own 3D model of the robot, and provides data logging capabilities.

As of now, the hardware design is nearly complete. Software has achieved WiFi AP broadcasting, TCP communications and work is starting on the Micro-ROS implementation. The design is fully open source under the GPL-3 license, and is hosted at *github.com/superrm11/VexDebugBoard* and *github.com/superrm11/VexDebugBoard_PCB*.