Rock Raiders — IGVC Design Report

Rensselaer Polytechnic Institute

Anomaly

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"I certify that the design and engineering of Anomaly by Rock Raiders during the 2018/19 year has been significant and equivalent to what might be awarded credit in a senior design course."

Glenn Saunders

Glenn Saunders | *Faculty Advisor* | saundg@rpi.edu

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1. INTRODUCTION

1.1. *Who We Are*

The RPI Rock Raiders are excited to enter the 28th annual Intelligent Ground Vehicle Competition. Our rover, *Anomaly*, has been modified from its original purpose of competing in the University Rover Challenge (URC) to autonomously navigate the IGVC course. As such, the rover's mechanical designs were developed not only for robustness but also to effectively utilize its navigation software. Anomaly's front wheel drive and caster arrangement is specifically designed for mobility in the new grassy terrain. With many overlapping aspects of the challenges, the electronics system was recycled and optimized, allowing the team to focus on the specific software challenges of this competition. Having an existing hardware framework of GPS, IMU, stereo camera, and encoder feedback structure, the software system employs a map creation, path-planning, and motor execution algorithm tailored for this competition. Overall, *Anomaly's* foundation as a URC rover and its adaptations for this challenge will ensure its success in IGVC.

1.2. *Organization*

Rock Raiders has five officer positions elected towards the end of every academic year: Team Captain, Vice President, Treasurer, Outreach Coordinator, and Project Manager. The project manager appoints mechanical, electrical, and software subteam leads, as well as any other subsystem leads as needed. Subsystem leads are responsible for managing the progress of their respective part of the rover and project manager is responsible for making sure all subsystems are progressing on schedule.

Team membership is often loosely defined; a few core members spend many hours each week and other members come and go from month to month. The consistent present team members and their estimated hours are listed in Table 1.

Team Member	**Major**	**Class**	**Estimated Hours**
Jack Corbin	Aerospace Engineering	Junior	176
Connor McGowan	Electrical Engineering	Sophomore	140
Shu-Nong Wu	Electrical/Computer Systems Engineering	Masters	356
David Michelman	Computer Science	Junior	356
Nishka Rao	Electrical Engineering	Sophomore	80
Adhikara Budhyartono	Aerospace Engineering	Senior	125
Siddharth Suri	Computer and Systems Engineering	Sophomore	130
Sam Ansaldo	Mechanical Engineering/Computer Science	Junior	70
Ruijie Geng	Computer Science	Junior	50
Owen Xie	Computer Science	Sophomore	50
		Total:	1533

Table 1. Team Members and Estimated Hours

1.3. *Design Process*

Rock Raiders follows a design process based around the various subteams that compose the team. Each subteam follows the same design process.

1.3.1. *Initial Determination, Design, Review*

To start, a required component or feature is determined, usually from the various rules for a competition. The entire team is required to read through the rules for competitions Rock Raiders competes in and anyone can suggest a feature/component to be designed. At weekly team meetings, the feature is proposed to the entire team, where it is decided whether or not to pursue designing something to achieve that feature. Once the team decides to pursue a design, the component is assigned to the subteam that best suits the nature of the component.

Once a subteam has been assigned a component, it is the duty of the subteam leader to assign it to a member of that subteam. For example, the mechanical subteam leader might assign a team member to redesign the wheels and the electrical subteam leader might task a member with creating a new battery harness. It is the responsibility of the member assigned the component to generate necessary designs, usually in the form of CAD files or electrical schematics. While the team member is designing the component, the subteam leaders and project manager continuously receive updates on the progress and ensure that designs will be finished within the necessary timeframe.

Once a team member finishes their designs, they are tasked with presenting finished designs to the entire team at weekly meetings. At these design reviews, the feasibility of the proposed design is discussed, along with possible suggestions for improvement. If any issues are noted, the team member is tasked with adjusting their designs to remedy the issues and then perform another design review. When nobody on the team has any issues with the design, the component is verified and parts and supplies will be ordered to create the component.

1.3.2. *Manufacturing/Iteration*

Once the parts and supplies arrive, the team member who designed the component is usually responsible for creating that component. The team works in a machine shop/lab environment with access to a variety of machining equipment. A large number of components on *Anomaly* were made in-house by members of our team. As with any good system, new components are rigorously tested to ensure that they are operating in the desired way. If any component doesn't meet the team's expectations, new alternatives are usually considered. The new alternative could be simple adjustments or complete system redesigns. Depending on the severity of the issue, components might be fully scrapped and started from scratch. Through this cyclical process of design, build, and test, our final vehicle is ultimately made better and the team's skills are likewise increased with each new iteration.

2. EFFECTIVE INNOVATIONS IN VEHICLE DESIGN

2.1. *Flexible Mechanical Design*

The overall design of the chassis emphasizes rapid prototyping and effective testing, through the dual battery setup, hand-built 80/20 frame, and removable sliding electronics box. The dual battery setup allows the rover to be powered by either a large lithium-ion battery or several smaller LiPo batteries. The large battery set up allowed for efficient testing and simulating the cinderblock weight and scale measurements. Using that battery, competition style testing could be done accurately. For competition, the smaller Lipo battery setup will be utilized to decrease the weight and condense the size of the rover.

The innovative hand-built 8020 frame enables the team to quickly change aspects of the rover and shape the modular design. Simple interchanging of wheelbases, axles, and gear ratios allows the rover to operate with any mechanical constraints imposed by the software. When point turning was found to require additional torque, the frame facilitated the easy attachment of a caster assembly and interchangeable gears.

An electronics case was custom-designed to protect sensitive electrical components from debris and weather. Since the team emphasized serviceability, the electronics enclosure was fashioned to easily slide out of the chassis when two clevis pins are removed. Compared to designs which fix the electronic components inside the chassis, this design enables the team to easily access and service any component.

While not a replacement for the wireless E-stop, a constantly connected wireless Xbox 360 controller serves as a secondary safety device. The software is set up so that if any input is received from the wireless controller then the autonomy system is disconnected from the drive system and control over the rover is given back to the operator. The operator must then press a specific button on the controller to give control back to the autonomy system. This makes assuming manual control over the rover incredibly fast and intuitive. It also allows the rover to be manually driven out of unwanted situations, unlike the wireless E-stop.

3. MECHANICAL SYSTEM

3.1. *Overview*

The team's current vehicle is aptly named *Anomaly*, due to the unusual circumstances of its creation. *Anomaly* was originally designed and built to compete in the URC and has been adapted in several key ways to compete in IGVC. Figure 1 shows *Anomaly's* configuration for competing at URC. The entire frame and chassis has been designed and hand-made by members of the team in our machine shop. Several of the key features and systems of *Anomaly* are outlined below.

3.2. *Chassis*

3.2.1. *Frame*

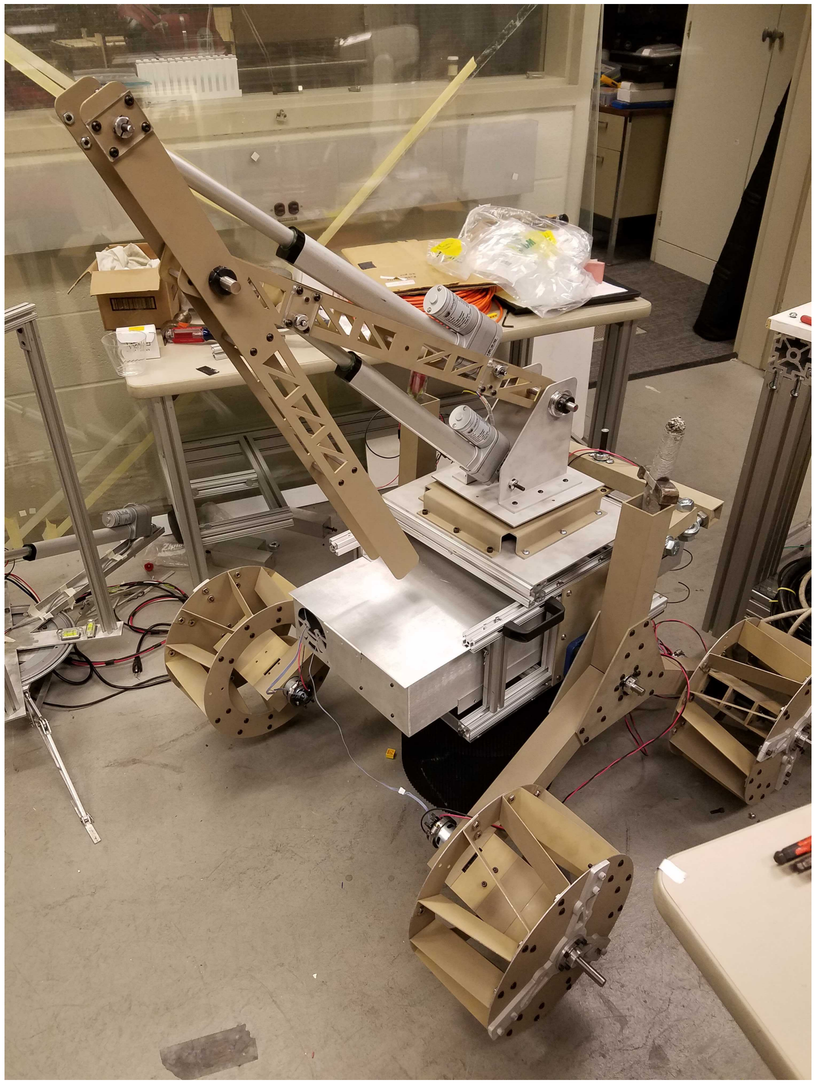

Figure 1. Anomaly in its URC Configuration

Anomaly's frame was initially designed to compete in URC, but has proven to be incredibly adaptable in working towards making the system IGVC ready. A large portion of this adaptability comes from the frame being primarily constructed in-house out of 80/20 aluminum extrusion. The 80/20 extrusion composes the bulk of the framework of the chassis, upon which all other systems are mounted. 80/20 allows *Anomaly* to be rapidly prototyped, built, and adapted. Rock Raiders has 24/7 access to a machine shop/lab space that allows the team to quickly and easily build new components that can be added to the 8020 frame. Figure 2 shows a cross-section of the type of 80/20 used in *Anomaly's* construction.

The frame has gone through extensive trial and error to produce a system that the team is happy with. Figure 3 showcases *Anomaly* during the transition to its IGVC configuration. Thanks in part to the ability to rapidly prototype new systems, *Anomaly* has gone through many iterations to make sure it is competition ready and strong enough to handle the necessary loads. Parameters like powered wheels, casters, center of mass, and gear ratios have all gone through several designs and changes that culminate in our final vehicle. Without the team's ability to design, machine, and install these changes on *Anomaly*, the vehicle would have taken much longer to achieve the progress it has so far.

3.2.2. *Drive System*

Anomaly boasts a unique drive system that was designed to carry it over the desert-like environments and terrain of Utah. Originally, *Anomaly* consisted of four independently driven wheels arranged in a rocker-bogie suspension.

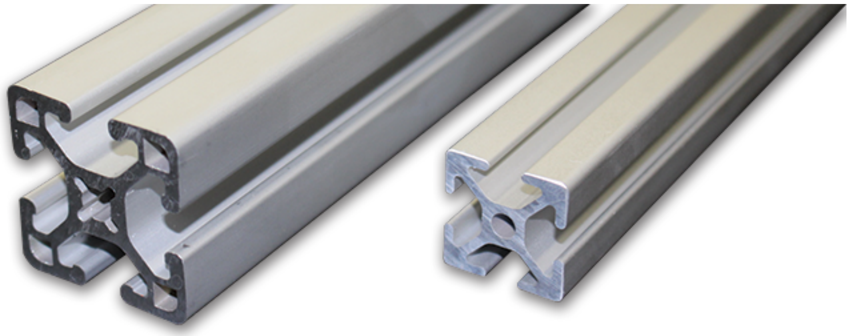

Figure 2. 80/20 Cross-Section

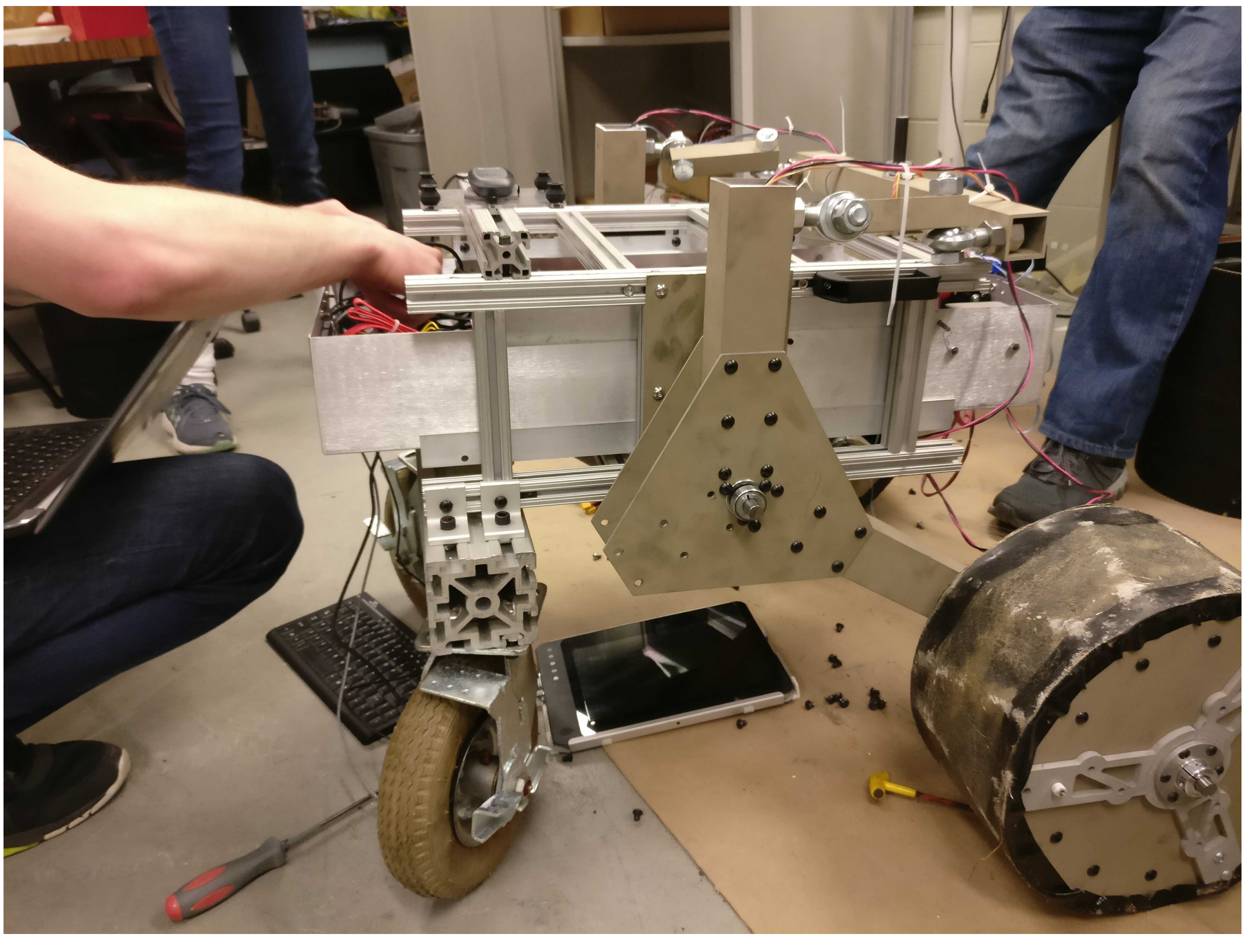

Figure 3. Transition to IGVC Configuration

While testing for IGVC, the team discovered that *Anomaly* was having trouble turning on grass in this configuration, so the drive system was adjusted.

Several iterations later, *Anomaly* now boasts two independent front wheel drive motors, with a large caster wheel on the rear. Each wheel is powered by a 12 volt AndyMark 775 RedLine motor with an 81:1 gear reduction through a planetary gearbox. During testing, the team tried changing parameters like the number of driven wheels, the wheel material, casters, and gear ratios. The current system allows *Anomaly* to efficiently grip grass to reach speeds of roughly 4.3 mph while maintaining the ability to perform incredibly tight turns.

Once the number of drive wheels was dropped to two wheels from four, the rocker-bogie suspension became more of a hindrance than a benefit. As such, the cross-bar for the suspension was anchored in place to the 8020 frame.

Anchoring the cross-bar allows the front drive wheels to remain rigidly attached to the frame, without free rotation about the center of chassis, and to maintain consistent contact with the ground. Without anchoring the cross-bar, the rocker-bogie suspension produced unwieldy results while trying to turn with the caster, resulting in loss of wheel contact with the ground. Fortunately, the frame and suspension were made in-house, so the team is able to quickly make small adjustments and changes like this.

3.3. *Electronics Enclosure*

A highlight of *Anomaly* is the electronics enclosure. The enclosure contains all electronic components on the rover and keeps them safe from the elements. The enclosure fits securely within the frame and is mounted to series of rails that allows it to be slid out from the frame, either from the front or back of the vehicle. The top of the enclosure is also removable to allow easy access to all the electronics. Several fans on the enclosure ensure that air is being circulated throughout the box, to prevent overheating of electrical components, especially the motor controllers.

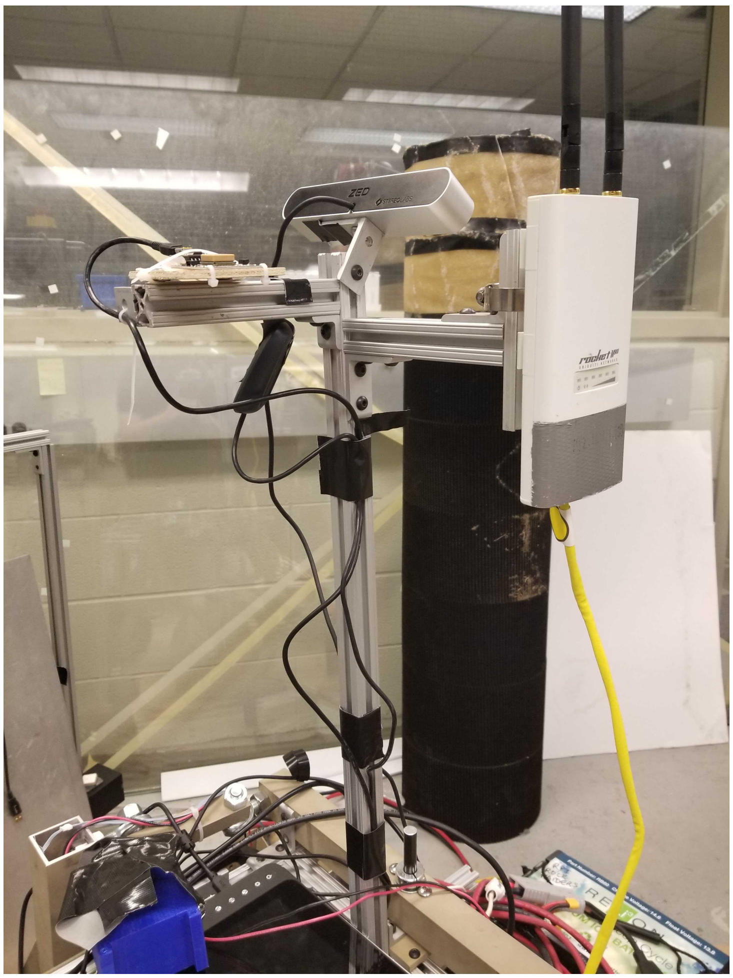

Figure 4. *Anomaly's* Communications Mast

3.4. *Comms Mast*

Similar to the frame, the communications mast is composed of 80/20 aluminum extrusion that is bolted directly to the frame itself and is pictured in Figure 4. The mast extends four feet above the ground and holds mission critical components such as a stereo camera, a GPS, and the communications radio. The mast is mounted to the frame at multiple points to ensure that the communications mast is rigid and secure to the frame.

The 80/20 construction allows us to easily change which components are mounted to the mast and where those components are located. The camera height and pitch angle has been one of the most commonly adjusted aspects.

The ability to make adjustments like this as the team needs them is what gives our mast a distinct advantage over ones with fixed locations for components. Moving components, adding components, even removing components takes almost no time and allows us to easily test a variety of configurations and setups, much in the same way our frame does.

4. ELECTRICAL SYSTEM

Anomaly's electrical subsystem relies on a set of eight 11.1V lithium polymer batteries to power an array of onboard computers, sensors, and the drivetrain. In addition to current-limiting circuit breakers, numerous emergency stop measures have been taken to ensure that should any electrical failures occur, there will be no damage to the rover or anyone around it.

4.1. *Power Sources and Distribution*

All components onboard *Anomaly* receive power from a collection of eight 3S 5000mAh lithium polymer batteries connected in parallel, providing 40Ah of charge and a nominal system voltage of 11.1V. These lithium polymer batteries can keep the rover operating at maximum capacity for approximately 28 minutes, and have been chosen to minimize battery weight. *Anomaly* can also accept power from a 12V 80Ah lithium-ion battery. This dual battery system has greatly aided the team in development. The larger battery can be charged while in use, greatly reducing downtime when maximum performance is not necessary.

After passing through the main circuit breaker and emergency stop contactor, the battery harness wiring is passed into a series of DIN rail terminal blocks, which distribute power to the rest of the rover. The power supply for our primary computer requires a regulated 12V input. To ensure that this input voltage remains constant, a buck-boost converter has been implemented. Several other onboard electronics, including the Arduino Pro used for the wireless E-Stop and the Nvidia Jetson Nano require a 5V input, so a 25W 5V buck converter has also been installed inside the electronics compartment for these devices. The GNSS receiver, IMU, and the Arduino controlling the indicator lights are powered from the main computer over USB, while the ZED stereo camera similarly receives power from the Jetson Nano. The only component incapable of running on 12V or 5V architecture is the Ubiquiti Rocket M9 radio used to transmit data back to the base station. This radio is supplied with 24V power over ethernet using a 24V boost converter.

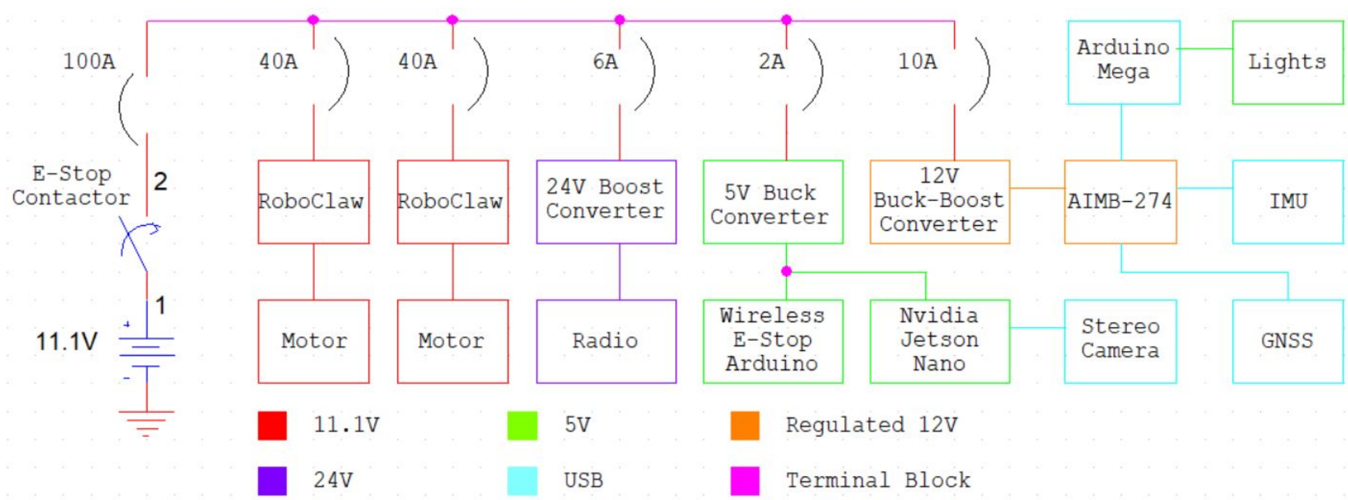

Figure 5. Power Distribution Diagram

4.2. *Onboard Electronics*

4.2.1. *AIMB-274 Single Board Computer*

All electronic components are interconnected via an onboard Advantech AIMB 274 mini-ITX computer. With a 3.2 GHz x86 processor and 16GB of RAM, this computer doubles the clock speed and memory of the popular Nvidia

Jetson TX2, allowing the team to more comfortably implement resource-intensive operations. This primary computer receives sensory feedback, including GPS and IMU data, and sends commands to the motor controllers through USB serial connections.

4.2.2. *Nvidia Jetson Nano*

To supplement the computational capabilities of the AIMB-274, the team has chosen to pair it with an Nvidia Jetson Nano. While the main computer handles path planning, kinematics, sensor readings, and motor commands, the Jetson Nano performs the processing necessary to generate a point cloud from the data obtained by the stereo camera, which is then transmitted to the AIMB-274 over Ethernet.

4.2.3. *ZED Stereo Camera*

Anomaly's primary form of sensory feedback comes from StereoLabs' ZED stereo camera. This device uses two high definition cameras to collect a three-dimensional map of the rover's surroundings. This data provides *Anomaly* with information about the location of obstacles in front of it, as well as images of the course, allowing it to detect both physical obstacles and the white lines bounding the course. The stereo camera is capable of 2.2K resolution at 15 frames per second and can see up to 20 meters in front of the rover. It is typically used at lower resolutions and higher frame rates.

4.2.4. *SAM-M8Q GNSS Receiver*

In order to navigate between the given GPS waypoints, *Anomaly* is equipped with a SAM-M8Q GNSS receiver from Sparkfun. Unlike GPS receivers, the SAM-M8Q can also receive signals from the Russian GLONASS, European Galileo, and the Chinese BeiDou satellite navigation systems. This sensor reports *Anomaly's* global position at 18Hz, providing the global path planner with a rough estimate of the direction in which the rover needs to travel.

4.2.5. *Adafruit 9dof IMU*

This nine degree of freedom inertial measurement unit is a combination of a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer, proving feedback about the rovers pitch, angular velocity, and directional orientation at all times. This IMU fuses the three separate sensors onboard and reports *Anomaly's* orientation in three-dimensional space.

4.2.6. *Motor Controllers*

As an interface between the main computer and the drive motors, the team has chosen to use IonMotion's 2x60A RoboClaw motor controllers. Each of the two drive wheels is driven by one of these motor controllers, which can supply up to 60A. In addition to their high current capabilities, the RoboClaws have numerous integrated features and software libraries, drastically simplifying their use. Beyond simple PWM control, the RoboClaws are capable of precise velocity control using a PID loop and are designed to directly receive quadrature encoder feedback without any additional hardware or programming. Furthermore, the RoboClaws can tune the PID constants automatically, allowing the team to avoid the lengthy process of finding the optimal settings. These motor controllers are even able to monitor motor current, voltage, and board temperature, automatically limiting the motor's current draw to safe values.

4.2.7. *Encoders*

Armabot's RS7 magnetic encoders are used to obtain wheel odometry. These encoders are mounted on the back of each drive motor and use a Hall effect sensor coupled with a magnetic puck attached to the shaft of the motor to determine its speed and direction. This data is transmitted to the motor controllers, which use the odometry as feedback for their PID loops. Wheel odometry is also sent to the main computer for state estimation.

4.3. *Safety Devices*

4.3.1. *Circuit Breakers*

To prevent any potential thermal runaway or short-circuit events, circuit breakers have been placed in series with every major component. The largest of these breakers is a 100A automotive breaker placed directly in series with the battery, ensuring that the system as a whole cannot draw more than 100A. Additionally, each motor controller, the main computer, and the voltage converters have their own individual breakers in order to prevent any of these critical components from becoming damaged in case of currents exceeding their ratings.

4.3.2. *Mechanical E-Stop*

The emergency stop functionality for *Anomaly* is implemented using a normally open automotive contactor rated for 120A placed in series with the main battery. Due to the placement of this contactor, the only component that does not need this contactor to be closed in order to function is the coil of this contactor. The contactor is controlled using a large red latching E-Stop button placed on top of the rover in series with the coil. When this E-Stop is pressed, the coil circuit is broken, opening the contactor and cutting off power to all other components.

4.3.3. *Wireless E-Stop*

Electrically, the wireless E-Stop is implemented in the same way as the mechanical E-Stop, using a contactor to cut *Anomaly's* main power. It does this using a latching relay placed in series with the mechanical E-Stop button and the contactor's coil. This relay is actuated by an Arduino Pro and 2.4GHz XBee radio module used solely for this purpose. Upon receiving the command to stop over the XBee, the Arduino will energize the reset coil of the relay, causing it to latch open, creating the same effect as pressing the mechanical E-Stop button. The wireless E-Stop also has a secondary feature used for development purposes that allows the operator to stop only the motors without disconnecting the main power by activating the emergency stop pin of the RoboClaw motor controllers. The operator can use either of these E-Stop modes by pressing the corresponding button on a hand-held remote, which sends the emergency stop signal to the rover using a second Arduino and XBee.

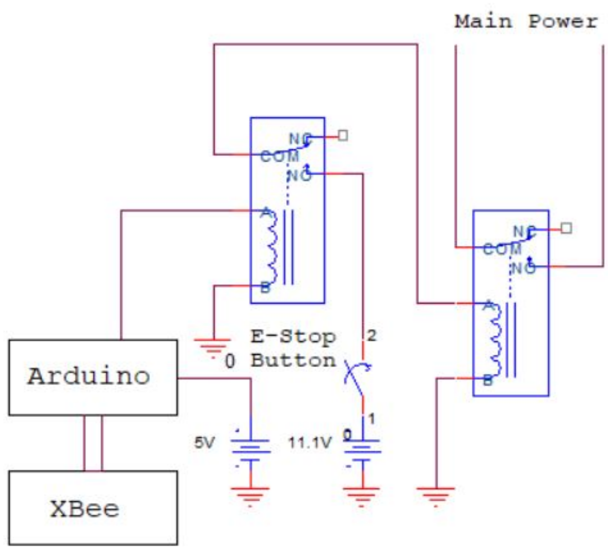

Figure 6. E-Stop Circuit

5. SOFTWARE SYSTEM

5.1. *Overview*

Anomaly utilizes the Robot Operating System (ROS) to interconnect various software components. This makes our software system highly modular and lets us use a wide variety of pre-existing software packages, such as the ROS Navigation Stack (NavStack). *Anomaly* heavily relies on the move_base package from the ROS NavStack.

5.2. *Obstacle Detection and Avoidance*

Obstacles are detected by our stereo camera. Data from the camera is turned into a colored 3D point cloud of the environment. Any points more than a set distance above the ground are considered to be obstacles and marked as such in the NavStack's costmap. The NavStack's planning algorithms can then plan paths around any viewed obstacles.

The lane detection system is more involved. Images of the lines are first projected from the cameras view to a top-down view. Images are then thresholded based on color and gradient in the x-direction. The two thresholded images are combined into a single image where only the lines and some noise are present. Histograms are taken of each

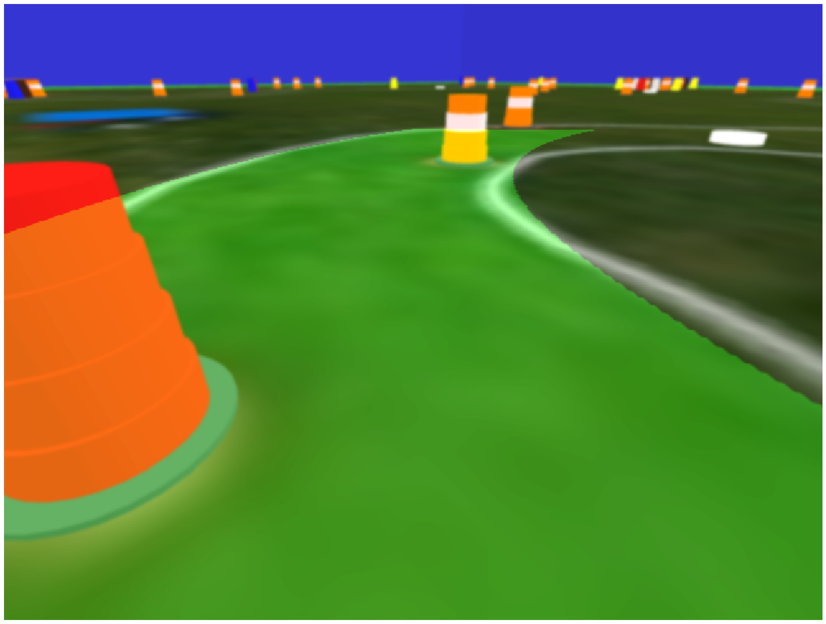

Figure 7. Lane detection in our simulated course

column in the image and the two peaks are taken as the locations of the left and right lines. Since the lines are not necessarily vertical in the image, sliding window detectors are used to trace the rest of the lines through the image. Potholes are identified by a Hough Circle Detector.

5.3. *Software Strategy and Path Planning*

Two path planners are employed, a global planner and local planner. The global planner plans a course through the entire costmap at a low frequency, typically once per second. The A* algorithm is used for this planner. The local planner runs at a higher frequency and is responsible for moving the robot along the global plan. For example, if the rover is a foot off course, then the local planner should correct for it instead of re-running the global planner. Our local planner uses a process known as trajectory rollout. At each time step it simulates the rover driving at many different forward and rotational speeds, then scores each trajectory based on how well it followed the global plan, how much closer it got the rover to the desired goal state, and how well it avoided obstacles. It then runs the highest scoring trajectory on the physical rover.

5.4. *Map Generation*

2D maps of the course are generated during each run for navigation purposes. Traffic barrels, potholes, and lines are all inputted into the costmap as obstacles the rover may not cross. Maps are not currently kept between runs, but the team is considering re-using maps between runs.

5.5. *Goal Selection and Path Generation*

Navigational goals are generated from the given sets of GPS waypoints. The global planner is responsible for finding a path through the map to each GPS waypoint. This approach was taken because of its simplicity and robustness; it makes the path planning process independent of the types of obstacles detected and how they are detected. It also allows the same path planners to be used while lane following and in no mans land. Since there are multiple goals in the course, a simple control loop is used to determine when a GPS waypoint has been reached and when the next GPS waypoint should be used. It operates as follows:

```
For each goal GPS coordinate:
    while the rover is more than two meters away from the current goal:
        wait
    Add a three-meter U onto the costmap behind the rover
    Select the next goal
```

The three-meter U keeps the path planner from deciding to drive backward through the course. The generality of the A* planner means that there is no elegant way to stop it from going backward through the course instead of forwards. The U stops this from happening.

6. DESCRIPTION OF FAILURE MODES, FAILURE POINTS, AND RESOLUTIONS

6.1. *Mapping Failure*

The stereo camera has been observed to rock back and forth while driving over rough terrain, sometimes mistaking large swaths of ground as obstacle. It is then often impossible for a path to the goal state to be planned. This is resolved by automatically clearing all observed obstacles from the cost map and re-planning a new path if no valid path can be found.

6.2. *Lane detection failure*

A highly probable failure mode is the lane detection system failing to identify the lanes. This could occur if lines are largely obscured by obstacles or if lighting conditions change. This is a hard failure mode to solve since lighting conditions, grass/line color, and the width of the line can vary wildly. Reliably detecting lines will likely include color-calibrating the line detection system on site before each trial.

6.3. *GNSS inaccuracies*

While our GNSS often reports positions accurate to a meter under ideal conditions, it has a tendency to drift by multiple meters when partially occluded, while still reporting small measurement uncertainty. This leads to instability in the state estimation since Kalman Filters use estimated uncertainty when deciding how much to "trust" each sensor. A partial fix is to artificially increase the GNSS uncertainty. We have also found our receiver to be sensitive to electrical interference. A few high noise components were removed from our rover to reduce electrical interference.

6.4. *Failure to turn*

Anomaly sometimes lacks the torque needed to point turn if the rear caster is not properly aligned with the direction of motion. We are actively moving the caster and center of mass to mitigate the issue. We may increase the gear ratio of the drive motors as a last resort but would prefer not to as it would decrease our driving speed.

6.5. *Motor Burn Out*

Our motors occasionally stall during testing, causing them to overheat and burn out on one occasion. The problem was mitigated by increasing airflow through the motor and adding stall detection in software.

7. SIMULATIONS

The team made a simulated version of the 2017 IGVC course based on a photo from the competition, and it has been an invaluable testing resource. The course was modeled in the Gazebo simulator, a commonly used robotics simulator with roots in the early 2000s. It has many graphical utilities for building robots and modeling the environment as well as a wide variety of publicly available plugins.

A large portion of software development and testing was performed in simulation. The simulated rover's software interface was designed to be identical to the actual rover's software interface so all rover code can be tested in simulation without modification. Additionally, great care was taken to have the simulated motors and sensors behave similarly to the actual motors and sensors. For example, the wheels on the simulated rover are the same size and spin at the same speed as on the physical rover. Point clouds generated from the simulated depth camera have the same resolution as point clouds from the physical camera. This allows almost the entire software stack to be tested in simulation as a single unit without modification.

In addition to testing the entire software stack, the simulator also makes testing individual components much easier. For example, instead of using the simulated GNSS and IMU for position data while testing the path planning system, exact positional data was extracted from the simulator instead. While not a representative test of real-world environments, such isolation testing makes tracking down issues far easier. Having optionally perfect simulated sensor data also takes away large amounts of uncertainty while testing. If results appear erroneous while testing with real sensors then fault could lie with sensor noise or a faulty algorithm. If results appear erroneous with noise-free simulated sensor data then an algorithm is definitively at fault.

Figure 8. A simulated rover in the 2017 IGVC course. The back wheels have no friction to approximate a rear caster

8. PERFORMANCE TESTING TO DATE

The majority of the non-simulated testing done to date has been integration testing. All rover systems are turned on and the rover is commanded to drive to GPS waypoints or follow lines until a system fails. Any subsystem that doesn't perform properly is then individually fixed and tested. The following rover properties have been observed/recorded through this testing scheme.

- Speed - *Anomaly*'s maximum speed has been measured at 4.3 mph, slightly lower than the maximum allowed speed of 5 mph.
- Ramp climbing ability - *Anomaly* has been observed climbing slopes greater than 15 degrees.
- Battery life - *Anomaly* can theoretically drive at full speed for 28 minutes using the smaller LiPo batteries. Experimental observations are roughly in line with this estimate.
- Distance at which obstacles are detected - *Anomaly*'s stereo camera's specifications state a maximum distance of 20 meters. However, any obstacles more than 10 meters away are ignored and the stereo camera has been observed producing point clouds with points more than 10 meters away.
- How the vehicle deals with complex obstacles including switchbacks and center islands dead ends, traps, and potholes) - This is where complete planning algorithms, like A*, shine. If there is a path through an environment then the planning algorithm will find it. Potential issues arise when the environment is not correctly observed, for example, if the depth camera tilts and sees the ground as an obstacle. If no path exists then recovery behaviors, such as clearing the costmap, kick in.
- Accuracy of arrival at navigation waypoints - Our GNSS receiver's accuracy varies between 1 meter and 2.5 meters. Given a fixed GNSS offset, our autonomy system would be capable of consistently driving to within half a meter of a GPS waypoints. The team is looking for ways to decrease GNSS inaccuracy.

An estimated breakdown of the *Anomaly's* cost has been broken down in table 2. The total estimated material cost to rebuild *Anomaly* is $4,727.00. However, many of these parts are left over from URC and are not strictly required to compete in IGVC. For example, two dual channel Roboclaw motor drivers are used because *Anomaly* once had 4 driven wheels. Since *Anomaly* now only has two driven wheels only one is necessary to compete in IGVC. This estimate also includes an estimated $767.82 in donated machining from Protocase.

Item	Quantity used	Unit cost	Total Cost	Item	Quantity used	Unit cost	Total Cost
11.75”x27”x4.1565” 1/16” 5052 aluminum electronics enclosure	1	$467.82	$467.82	2 Position Feed Through Terminal Block Connector	1	$5.53	$5.53
1” High x 1-1/4” Wide x 4’ Long 6061 Aluminum T-Bar	2	$7.43	$14.86	DIN Rail	1	$10.83	10.83
3/16” Diameter Steel Clevis Pin	4	$6.80	$27.20	5 Port Gigabit Network Switch	1	$16.99	$16.99
Zinc-Plated Steel Cotter Pin	4	$5.49	$21.96	AIMB-274L-00A1E Motherboard	1	$308.00	$308.00
1”x1”x6’ T-Slotted Framing	2	$17.60	$35.20	Power Over Ethernet Injector PCB	1	$19.11	$19.11
Assorted Aluminum Rectangular Tubing			$59	5 feet cat5e cable			$4.99
5/8”-18 Ball Joint Rod End	4	$9.94	$39.76	Roboclaw 2x60 Motor Controller	2	$199.95	$399.90
AndyMark 775 Redline Motor	2	$18.00	$36.00	Ubiquiti Rocket M9 Wireless Access Point	1	$187.77	$187.77
Versa 81:1 Planetary Gearbox	2	$94.94	$189.88	900 MHz Dipole Antenna	2	$20.00	$40.00
1/2” Keyed Set Screw Shaft Coupling	2	$14.77	$29.54	2 Position SPST Keylock Switch	1	$8.76	$8.76
1/2” Cast Iron Mounted Ball Bearing	2	$52.40	$104.80	Red E-stop Push Button	1	$115.00	$115.00
Assorted Fasteners			$50	4 Port USB 3.0 Hub	1	$11.87	$11.87
Black Plastic Pull Handle	4	$6.40	$25.60	Assorted molex connectors			$20.00
Wheels	2	$150.00	$300.00	RS7 Encoder	2	$25.00	$50.00
1/8”x1’x2’ Aluminum Stock	4		188.44	Zed Stereo Camera	1	$449.00	$449.00
Turnigy 5000mAh 3S 30C Lipo Battery Pack w/XT-90	8	$33.63	$269.04	SparkFun GPS Breakout - SAM-M8Q	1	$39.95	$39.95
XT90 Male to XT60 Female Adapter	4		25.36	SparkFun FTDI Basic Breakout	2	$14.95	$29.90
6 gauge ultra flexible battery wire-Red			$90	CPU & Chip cooler	1	$32.89	$32.89
16 gauge stranded building wire			45.42	Samsung 850 EVO 120GB Solid State Drive	1	$118.99	$118.99
12V DC SPNO Solenoid	1	$24.35	$24.35	PicoPSU-160-XT 12V DC-DC 24-pin ATX Power Supply	1	$89.99	$89.99
100A Circuit Breaker	1	$72.66	$72.66	40A Circuit Breaker	2	$20.09	$40.18
Power Distribution Block	1	$45.26	$45.26	16A Circuit Breaker	7	$20.09	$140.63
5V 25W DC-DC Converter	1	$17.50	$17.50	Intel i7-4790S	1	$203.02	$203.02
12V to 24V 240W DC-DC Converter	1	$18.72	$18.72	8gb SODIMM memory	2	$32.99	$65.98
12V Buck-Boost Converter	1	$20.43	$20.43	Nvidia Jetson Nano	1	$99.00	$99.00

Table 2. All materials used in *Anomaly*