Dokalman

University of Cincinnati

26th Annual Intelligent Ground Vehicle Competition

Joseph Knight ✦ Tony Iacobelli ✦ Joe Hirschfield ✦ Douglas Flick ✦ Lucas Boswell
Alex Suer ✦ Matt Thomas ✦ Clay Curran ✦ Amanda Mitchell ✦ Jordan Jacob
Sam Heyl ✦ Sam Oakes ✦ Evan Baumann

Contact Information for Team Members provided in Team Organization

Submitted 5/15/2018

CERTIFICATION:
I certify that the engineering design in the vehicle Dokalman (original and changes) by the current student team identified in this Design Report has been significant and equivalent to what might be awarded credit in a senior design course.

Janet Dong
Doctor Janet Dong, Advisor

Introduction

The University of Cincinnati Robotics Team has a proud tradition of competing in the Intelligent Ground Vehicle Competition, starting with the Bearcat Cub in the 1st Intelligent Ground Vehicle Competition. The first iteration of Dokalman was entered in the in the 22nd Intelligent Ground Vehicle Competition. In the four years since its original design, robot has been completely re-designed and are now on our fourth iteration of this robot. The following list of improvements have been made since the last IGVC competition:

- There were various improvements to the physical arrangement of the robot:
    - The drivetrain was completely reworked, moving from an open chain gearbox to an enclosed gearbox (designed in-house), squaring the axles.
    - New encoders were added to increase precision and handling.
    - The mast was completely redesigned to accommodate new hardware which is detailed below.
    - A new differential GPS unit was purchased and mounted to the mast via a custom designed bracket.
    - New wide angle cameras and IMU were installed.
    - New outer panels were implemented for increased weatherproofing and thermal displacement.
    - A new signal light was designed to give better indication of the robot's actions.
    - Bolts and fasteners were standardized to reduce the number of tools needed to service the robot.
- 3D modeling along with rapid prototyping techniques were heavily leveraged to create custom parts. New parts to Dokalman this year are:
    - Camera mount with rain cover was created to accommodate the new cameras while simultaneously increasing the waterproofing of the robot.
    - An IMU case was engineered and printed for stable mounting to Dokalman, which reduces fluctuations in data due to erroneous vibration.
    - Gearboxes were fabricated via laser cutting to allow a custom drivetrain optimised off-road navigation.
    - The outer shell was fabricated via laser cutting increase water resistance as well as better thermal management. Unofficial testing revealed that the weatherproofing performs at at least an IP-42 level.
- There were various software changes to accommodate hardware changes, as well as new features
    - The navigation stack was re-written to take heading information from the differential GPS instead of the Inertial Management Unit.

- JAUS functionality was added to the code base to compete in the IOP challenge.
- Vision code was re-written to minimize distortion from the wide angle cameras.

The function of these changes is further explained in the following sections describing the control and hardware system design for Dokalman.

Team Organization

Unlike last year's smaller competition team, this year's team incorporated many new members with a focus on knowledge transfer and cross training, as this is the last year for many of the original architects of Dokalman. Team members were able to carry out full life cycle development as the robot progressed from prototype to end product. Coordination between roles was perpetual as each constituent layer of the design was worked on simultaneously.

Role	Name	Major	Email*	Grad Year
Captain/Lead Engineer	Evan Baumann	Mechanical Engineering	baumanea	2020
Software Lead	Joseph Knight	Computer Engineering	knightjp	2018
Vision Lead	Douglas Flick	Computer Science	flickdm	2018
Navigation Lead	Joe Hirschfield	Computer Science	hirschjb	2019
JAUS Lead	Sam Oakes	Computer Science	oakessa	2022
Network/Logistics Lead	Tony Iacobelli	Information Technology	iacobeaj	2019
Electrical Lead/Vision	Lucas Boswell	Electrical Engineering	boswellj	2018
Wiring Lead	Jordan Jacob	Computer Engineering	jacobjr	2020
Distortion Lead	Alex Suer	Mechanical Engineering	suerad	2022
Procurement Lead	Matt Thomas	Computer Science	thoma3mw	2018
Mechanical Lead	Clay Curran	Mechanical Engineering	curranct	2022
Electrical Engineer	Amanda Mitchell	Electrical Engineering	mitch2an	2022
Weatherproofing Lead	Sam Heyl	Computer Engineering	heylse	2022

*Note: Emails are suffixed username@mail.uc.edu

Design Process

This year the team built off of the successes and lessons learned from the previous competition. The previous iteration of Dokalman had major issues obtaining a reliable heading. In order to solve this problem, a differential GPS was acquired to effectively eliminate this issue. Furthermore, a total rehabilitation of the mechanical systems and physical design was performed to increase the longevity and reliability of the physical parts. Modifications to the various parts of the robot were carried out simultaneously by the various sub-teams. Teams worked closely together in order to coordinate interconnected components and the boundaries between design layers to eliminate as much down time to as possible. The break-fix design methodology used this year resulted in more time to integrate these systems in software.

Innovative Concepts and Technologies

Some of the new and innovative concepts that we included into this year's design are as follows:

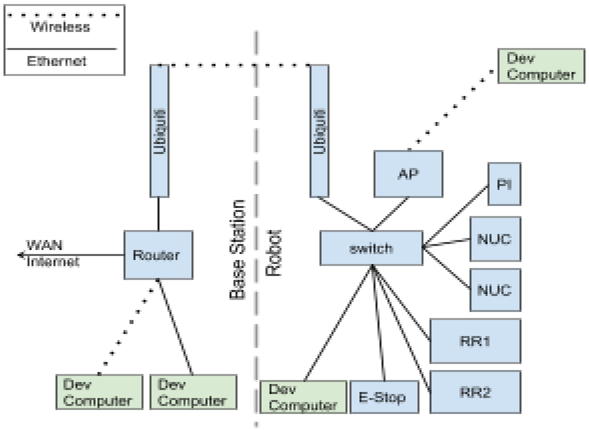
Drivetrain

Dokalman's new form this year is a direct result of the significant effort placed on durability and reliability. Sponsorship by Flood Heliarc resulted in expanded metalworking capabilities to manufacture the custom drivetrain with a high level of precision. This has allowed the team to better use its CAD/CAM abilities to their fullest potential. The increased precision and reliability in the robot's performance are a direct result of this sponsorship.

The new gearboxes presented a natural opportunity to upgrade the encoders present on the robot. The new gearbox which allows for greater precision, speed, and maneuverability with significantly reduced backlash. This gearbox also gives Dokalman a much higher level of durability and safety due to the new closed gearbox.

The team have also used the new manufacturing capabilities to create new outer panels, new mast, and new electronics shelf. The new aluminum outer shell dive Dokalman better temperature control during long days in the sun. New aluminum mast and mounting allow for quick and rigid mount to the steel frame.

Network System Design



A majority of the sensors on Dokalman communicate using the TCP/IP protocols. This ensures reliable, scalable data communications that are relatively easy to debug, forming the design goals of this network. Devices on the robot communicate with each other via gigabit ethernet, via a layer 2 switch. This network, when not running in competition mode, is bridged to our base station network for the purpose of easy, reliable access by developers. This occurs via a Ubiquiti long distance 2.4 GHz network link. This allows multiple developers to connect to a stable network without having to follow around right behind the robot. In practice, this also allows developers to be located in shade and with available power, thus extending the amount of time that can be spent actively working on the robot. Network segmentation was implemented this year to decrease latency each segment and increase the quality of core services delivered within the network. Core services, such as DNS, DHCP, NTP, and routing were all significantly improved by this change resulting in a more stable foundation for the ROS framework to work with. The 2.4 GHz Ubiquiti long distance uplink on the base station was upgraded to a directional antenna, reducing interference from other wireless networks and improving network range to approximately 400 feet. Furthermore, the use of non-standard 802.11 channel mappings have ensured that this network is more resilient against channel exhaustion common with in the 2.4 GHz spectrum. Persistent time synchronization, latency, and connectivity issues have been eliminated by this network redesign.

Mechanical Design

Drivetrain

The expanded manufacturing capabilities that the team acquired this year directly resulted in a new gearbox. This gearbox was made with off the shelf gears and custom made mounting and shafts to hold it together. The gear box is sealed and grease packed to improve long term durability, as well as keep debris out. Brass bushings were replaced with ball bearings to improve the efficiency of the gearbox. The custom gearbox allowed the team to pick the perfect gear ratio. We picked a ratio of 24:1 to give us a top speed of 5.45 MPH and enough torque to climb inclines up to 35 degrees.

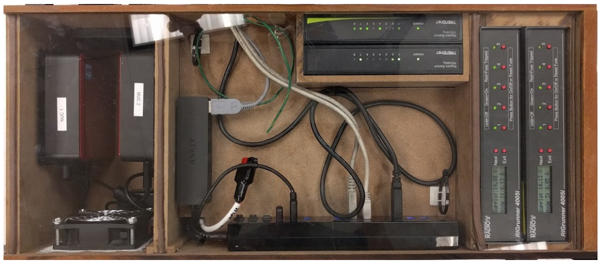
Frame Design

Building upon the success of last year's CAD modeling efforts, this year's hardware team further refined the frame and shell with the goal of achieving greater reliability and weatherproofing. Laser cutting was used to create a new mounting system for our new mast (which is now made of 1 inch square aluminum), which consists of a fabricated bracket to easily mount it to the steel frame using carriage bolts. The two batteries were moved back to move the center of gravity over the drive axles.

Weatherproofing

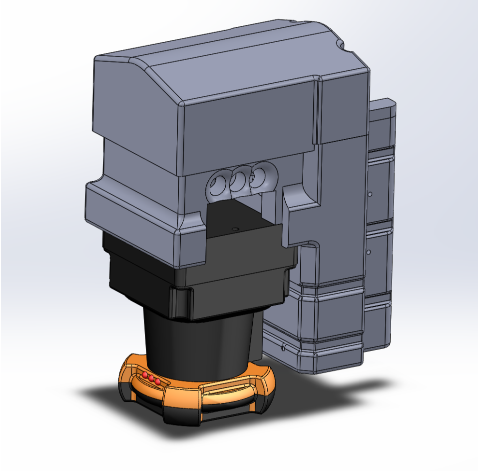
Dokalman can operate in all but the most severe weather conditions. There are multiple tight fitting panels used to keep the water out of the electronics in addition to a custom raincoat. Special attention was placed in the design to direct any water that may enter the robot away from non-weather resistant components. This allows for redundancy in water protection should the raincoat become compromised. Further protection from water and dust are provided by a custom electronics enclosure, detailed below. Parts outside of the panels are kept in or under enclosures, or are water resistant on their own.

Electronics Enclosure



A project box was constructed to centralize and protect all core electronic components. Power distribution, conversion, network switches, computing resources, and USB hubs are located within the box. Special attention was given to the thermal, cable, and power needs of each component within the box. The optimized layout reduced the total footage of cable on the robot as well as increased serviceability by making components easily removable as all components are pressure-fitted. The two-layer design enables distinct cooling zones to enable thermal separation of the hottest components. The ventilation system also employs filters to ensure that dust, pollen, and dirt do not coat the electronic components.

3D Printing

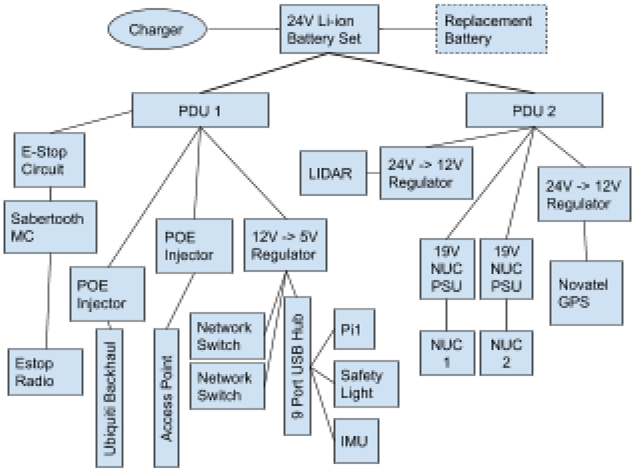


For many of the components which were not made of steel or aluminum, 3D printing technology was utilized. Among the pieces that were modeled with Solidworks, Sliced with Simplify3D, and printed using a Genuine Prusa i3 Mk2s and RepRap Prusa i3 printer were the cases for electrical components and various mounting brackets. The ability to custom-design these 3D printed components added a layer of protection and specialization which would have been difficult to achieve otherwise. Furthermore, we lowered cost by using 3D Printing as PLA plastic filament is significantly less expensive than the raw materials that would have been needed to mill the same parts. The model pictured left is the custom designed and fabricated lidar mount with a representation of the lidar unit as well.

Suspension

Due to the lower speeds and low grade of the terrain that the robot is designed for, a suspension was determined to not be needed. Further time and financial constraints made the design and implementation of a suspension not feasible in this iteration of the robot.

Electronic and Power Design



The electrical design for Dokalman was driven with several goals in mind, many based on difficulties in previous designs. The central batteries connect to the 2 Power Distribution Units (PDU) which then connect to all the powered systems on the robot. These PDUs have the ability to enable and disable all the individual components on the robot, as well as read their live current load. Incorporated in the PDUs are slow trip electronic fuses, which cut the current if a configurable current limit is passed. The biggest advantage of the electronic fuses is that they can be easily reset, which allows us to set very close tolerances to protect the devices.

From a hardware perspective, we have mounted all the electronics to a single board that allows us to service the frame by removing the single board and not disconnecting all the components. This board, made of MDF, also serves to electrically isolate the devices from each other.

One important aspect of the robot's design was strictly working with DC voltage. In past experience using inverters and A/C adapter leads to wild voltage zero points and dangerous behavior when connecting non-referenced sources together, such as computers and sensors. In Dokalman, all voltages are relative to battery negative, and there is no alternating current to cause the floating grounds. This achieved both by careful part selection and the use of DC to DC step up and step down converters, for 18V and 5V devices, respectively

With the improvements made to power distribution, the robot can operate in competition mode for 3-4 hours of continuous use. However, in lower functionality mode, Dokalman can last significantly lower. The largest power demand for the robot are the NUC computer cluster and the motion controller. If the robot is running at idle, without moving, it will last for 20 hours running the master controller and networking gear.

Wireless E-stop System Design

Dokalman's estop system was upgraded this year to be simpler and better integrated into the robot's electrical system. When the wireless e-stop switch is pressed, or the e-stop switch is out of range, a dedicated e-stop AVR disables the robot's motion controller by disabling the power channel on our power distribution board. This prevents powered motion, and the motors bring the robot to a sudden complete stop in a fail-safe manner. The advantage of this system is the fact that the control system can detect the disabled motion controller and stop the software from commanding motion as well as displaying an e-stop warning on the safety light.

Software Design

Dokalman is built using the ROS, or Robot Operating System, framework. ROS specifies a method of data exchange between independent software codebases working in a network to control the robot's position. ROS fits within the team's development style because it leads to concurrent development, test isolation and well compartmentalized code.

Navigation System Design

The navigation system is a multi-level software system designed to and store the robot's location, as well as the locations of all obstacles around it. By recording the entire environment into a virtual map, smarter pathfinding decisions can be made.

The lowest level of localization focuses on aggregating wheel encoder and accelerometer data to generate accurate odometry for the robot. The wheel encoder data is passed through an extended kalman filter combined with the output of a 3D accelerometer to detect slippage during acceleration and braking. To correct for drift in the robot's overall localization, the LIDAR and GPS are used for position correction . All combined, the odometry allows the robot to continuously evaluate its position relative to start.

GPS System Design

To orient dokalman in respect to its physical location over time, Dokalman is equipped with Flexpak6D GPS receiver with two differential Vexxis GNSS-502 amplified antennas. Via multiple serial interfaces virtualized over a USB connection, software on the robot decodes several NMEA messages to derive the robot's current latitude, longitude, and heading. This information is parsed every second. This GPS location and heading is inversely broadcast as a descendant of the map frame of the robot, to prevent reparenting of the fixed map frame. With this transform, any other UTM coordinate can be translated to a relative transform from the robot. Using this system, the waypoint finding node simply attaches UTM translated goals in this frame for the robot to navigate.

Map Generation

Once Dokalman has an accurate reference to its location, the map can be used to record the position of obstacles in the course. A costmap approach is used to track the positions of obstacles such as lines and barrels. The LIDAR detection layer takes in laser sweeps of the surrounding area. A separate layer takes in the visible lines from both camera systems mounted on the mast, allowing the cameras to work together to build a complete map. This costmap is persistent during the run, and is continuously built and refined as the sensors discover new areas of the world.

Pathing Planning

To plot a route through the costmap, the robot takes a 2 step approach. The global planner, which takes a low resolution view of the entire known map, uses a modified A* route planning approach to set intermediate goals from the robot’s present location to its final goal. These intermediate goals are delegated to a local planner to achieve, which takes a higher resolution look both at the environment in the immediate vicinity of Dokalman, and at the shape of Dokalman itself. It is this layer that handles the back out logic described below in failure modes.

Goal Selection

To set the global goals, dokalman is programmed to find GPS waypoints in the order to match the course. However, we added additional limitations to its route planning strategy analogous to horse blinds. To the route planning algorithm from driving straight at the exit of the maze at the beginning of the run, the goal setting limits the turning radius for the global plan to force dokalman to drive forward and make the first corner. This radius also prevents backtracking or turnarounds in the maze, without preventing error recovery behavior in the local plan.

Obstacle Detection and Avoidance

Through the use of our two costmaps, various sensor data can build a virtual world that describes the real world with associated “costs.” This allows the robot to see objects and make decisions about them such as the likelihood of running into an object. We can essentially compute a bitmap where each pixel has a threshold for the how close we can get to an obstacle without hitting it.

Vision System Design

Loads the Cameras and sets runtime parameters.

Corrects the distortion due to 130° radial lens for each camera.

Detects lanes and projects the image onto a real world coordinate system.

Camera Driver

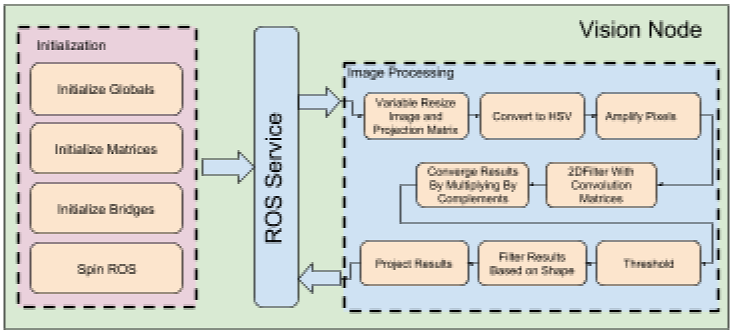
Dokalman utilizes the ROS Ecosystem for the camera driver. In particular we use the usb_cam node which integrates nicely into most V4L USB Cameras. This year the team decided to move away from the C920 Webcams dokalman has used in the past and towards the dual 130° Action Cameras because in the previous year dokalman was unable to see the lanes before it was already on them. The usb_cam node provided a seamless plug and play experience for upgrading the new cameras.

Distortion Correction

Unlike the C920 Webcams used previously, the Action Cameras have a large amount of distortion due to the 130° radial fisheye lens. The advantage to this is the greater field of view allowing us to see a larger amount of the field and see objects further away and to the sides of Dokalman. Due to the distortion the fisheye lens Dokalman needs to correct each frame such that the projection of the frame matches its real world coordinates.

Image Processing

Dokalmans line detection algorithm never works on the full sized image given to it. Information is purposely lost or gained based on lighting conditions. Convolution Matrices are used for edge detection and then filtered to let in fewer or more detected shapes. Dokalman never really looks for straight lines but actually expects the line to be misshapen and returns contours. Finally the contours are then projected in the final result.



IOP System Integration

Dokalman utilizes the JAUS++ open source library provided by the University of Central Florida's ACTIVE Laboratory. Using JAUS++, we were able to implement all of the IOP challenge requirements into Dokalman's ROS framework. While JAUS++ handles non-robot specific features such as discovery, we integrated robot specific JAUS requirements into the ROS framework, such as position reporting, velocity reporting, waypoint navigation, and remote control.

Failure Handling

Software Failure

Failures in the software mapping algorithms are most often manifested as ghost obstacles detected and tracked by the planners but do not actually exist in the real world. This is caused by the occasional bad read from the LIDAR, or from line shaped items detected by the vision system. We correct for this by allowing the sensors to clear out obstacles previously recorded if they are no longer present when returning this position. This fits well with the navigation's fallback strategy for impossible navigation tasks.

When the route planner can not find a route through a local costmap, it defaults to a backout and spin behavior. In our experience, unplannable maps often contain non-existent obstacles. Reversing and spinning slightly gives the cameras and lidar a new perspective on the environment so that the map can be cleared out and a proper route planned.

Electrical Failure

Electrical faults are most often caused by current overdraw from the motor controller. While the system is rated to a very high current load, we have limited it with a software fuse to a specific maximum current to protect the batteries and drivetrain. If the robot is up against a immobile obstacle and attempts to move forward, it will trip the circuit and be estopped until the circuit is re-enabled.

Vehicle Safety Design

In additional to preventing significant current in a motor stall configuration, care was taken during the design phase to enclose chains and gears inside the closed gearbox and underneath the shell of the robot to prevent dangerous pinch points and hazards. To work on the drivetrain, we can remove the mast, batteries and electronics package and flip the entire chassis over to access the equipment underneath.

Simulation

Simulation was done by creating a virtual machine on a proxmox server and looping sensor data over various interfaces. The benefit to using proxmox is that it is open source software with no vendor lock-in and allows for compartmentalization. Using

Proxmox we could clone a base image and produce copies all of which were identical to our competition machine. Each machine could easily be managed from a simple web interface and allowed users to have access to a linux machine. From this programmers of all levels and knowledge could get exposed to linux and even if they managed to damage the underlying system we could easily roll-back the machine to a stable state.

Much of our sensor data had been recorded during a prior run and looped on the system. Custom udev rules were written to loop the sensor data over the same names as the devices the competition robot would have. For example Video Feed was looped and users could subscribe to a constantly running feed of what competition would look like. Complete with Ohio weather that changes every 5 minutes (Normal Real time Behavior) so that the environment is dynamic.

The reason we chose this method was due to time constraints, finances, and greater control over our simulation setup. This does not require a machine with a graphics card nor does it limit our developers from having to worry about destroying the machine they are working on due to a lack of experience with linux. Developers are encouraged to learn more about linux through trial and error.

Performance Testing

All the critical systems on Dokalman were tested in isolation before added to the robot. A list of systems below had specific test strategies.

Gearbox and drive system - Bench tested with 8020 frame and grades. Design was limited by the traction of the surface under the wheels. Electrical measurements fell in expected range for the components used. 24V was selected for superior torque for a given current.

LIDAR system - tested on independent wheelchair robot in various lighting and distance configurations.

Vision system - Several different webcam models were tested, and the mobius action camera was selected for its onboard encoding and wide field of view. The vision pipeline was designed to input and output video at several points to allow sections to be tested individually.

Wireless Performance - Dokalman has a variety of sensors relying on means susceptible to RF interference. A Software Defined Radio (SDR) was used to locate and isolate sources of RF interference on the robot. Appropriate steps, such as adding ferrite cores and upgrading to shielded cabling were taken to address areas that were particularly noisy.

Performance Assessment

Our testing shows successful route planning and obstacle avoidance for barrels and lines. Dokalman can find GPS waypoints accurately to within 0.6 meter for the center of the robot, functionally hitting the target waypoints. A lack of ideal proving ground has limited our ability to test fencing and potholes. Our self navigation averages a 1 m/s speed when making straight lines or slight turns. The route planning loop occurs at a 20Hz rate, so robots reaction time is limited by acceleration and deceleration limits rather than planning frequency. Obstacles can be added as soon as they are detected by the sensors. For the LIDAR, this can range as far as 30 meters for a reflective object with a 270 degree viewing angle. The vision system can see 160 degrees side to side for about 6 feet out from the robot. The robot has been tested at full weight on a 35 percent concrete slope without slippage or stall.

Appendix A: Bill of Materials

Part	Manufacturer	Model No	Quantity	Unit Price	Total
Frame	Alro	1” steel square tube	360 ft	$360.00	$720.00
Batteries	Smart Battery	SB100	2	$1300	$2600
Motors	AmpFlow	F30-400	2	$200.00	$400.00
Motor Driver	Sabertooth	TE-091-260	1	$190.00	$190.00
Processing Computers	Intel	DC3217BY	2	$1,000.00	$2,000.00
Master Computer	Raspberry Pi	2B	1	$35.00	$35.00
Cameras	Modius	Mini Sport Cam	2	$69.99	$139.98
Wireless Estop	3Built	RES12VU	1	$74.99	$74.99
Motion controller	Kangaroo	X2	1	$23.99	$23.99
GPS	Novatel	FlexPak6D and antenna	1	$3600	$3600
Gearbox parts	Vex Robotics	n/a	2	$150.00	$300

Lidar	Hokuyo	UTM-30LX-EW	1	$5200	$5200
Networking equipment	Ubiquity	Ubiquity	1	$200	$200
RIGrunner	West mountain radio	RIGrunner 4005i	2	$280	$560
DC Transformer	RioRand	RRDCCI12245V5A25W	2	$15.00	$30.00
Wheel Encoders	CUI inc	amt102-v	2	$25.00	$50.00
Controller	Sony	Dualshock 3	1	$44.99	$44.99
Body Panels	Flood Heliarc	n/a	1	~$1000	$1000
Misc 3D Printed Parts	n/a	n/a	4	$15	$60.00
				Total	$17,228.95

Acknowledgements

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