APOLLO IV: IGVC 2018 Design Report
Bluefield State College

Submitted: May 15, 2018

Team Captain:

William Lambert
lambert_cw@live.bluefieldstate.edu

Team Members:

Shonté Cargill
cargill_st@live.bluefieldstate.edu

Samuel Stephens
stephens_sr@live.bluefieldstate.edu

Kristen Hogan
khogan@bluefieldstate.edu

Jesse Edwards
haynes_je@live.bluefieldstate.edu

Evan Rees
rees_em@livebluefieldstate.edu

Samuel Bauer
bauer_se@live.bluefieldstate.edu

Adam Hammond
hammond_ac@live.bluefieldstate.edu

Ryan Heimer
heimer_re@live.bluefieldstate.edu

Danielle Fowler
fowler_db1@live.bluefieldstate.edu

Kyle Wolfford
wolford_ka@livebluefieldstate.edu

Ben Helmandollar
helmandollar_bt@live.bluefieldstate.edu

Avery Holliday
holliday_avery@live.bluefieldstate.edu

Statement of Integrity:

I certify that the design and engineering of Apollo IV by the 2017/2018 BSC robotics team has been significant and equivalent to what might be a senior design course.

Joseph Hazelwood

Joseph Hazelwood, Faculty Advisor

1 INTRODUCTION

The Bluefield State College (BSC) Robotics Team is proud to enter Apollo IV into the 26th annual Intelligent Ground Vehicle Competition (IGVC). Apollo IV is updated from the 2017 Apollo III and is designed to autonomously navigate an obstacle course for IGVC. It has been significantly upgraded and improved over its predecessors. Apollo IV utilizes a powerful sensor suite, innovative electrical and mechanical systems, many modular system designs, and is developed to adapt to a plethora of scenarios. Due to the past experiences with the IGVC competitions, the team's testing shows that Apollo IV is well prepared to perform in the competition. This report describes the details of the design of Apollo IV.

1.1 TEAM ORGANIZATION

Apollo IV was developed and constructed utilizing the different engineering technology fields offered at Bluefield State College. The team is structured using a "military hierarchy". The team captain is chosen each year as the person with the most experience and greatest knowledge of the robot, including its electrical, mechanical and software systems, and the annual competition. This decision allows the team's focus to be on the enhancement of the robot's performance at IGVC. The team captain is responsible for overseeing the design and development of all systems in the robot. The mechanical, electrical, and computer science teams are then headed by an individual team leader who is the most experienced person in that specific field. Team leads are responsible for guiding the development of all systems in their specific field and communicating with the team captain and other team leads. Team members participate and are involved in development, design, fabrication, and maintenance of the robot.

The electrical team focuses on designing all power distribution systems, electrical circuits and components, ensuring that the sensors are accurately and safely integrated into the system, and ensuring safety of the vehicle and operators. The mechanical team designs hardware for integration of sensor systems and ensures the physical structure of the robot is robust, effective and efficient. The computer science team is responsible for the development of software systems and calibration of sensors to convert raw data to ensure accurate navigation. The team invested over 2,285 hours in the development of Apollo IV as shown in the table below.

Areas of Concentration					
Team Member	**Academic Major**	**MECH**	**ELEC**	**COMP**	**Hours**
William Lambert (Team Captain)	Mechanical/Electrical Eng.	X	X	X	640
Shonté Cargill (Electrical Lead)	Electrical Eng.		X		550
Sam Stephens (Mechanical Lead)	Mechanical Eng.	X			125
Kristin Hogan (Comp. Sci. Lead)	Computer Science			X	125
Jesse Edwards	Mechanical Eng.	X			32
Evan Rees	Electrical Eng.	X	X	X	430
Samuel Bauer	Mechanical Eng.	X	X		85
Adam Hammond	Electrical Eng.		X		85
Ryan Heimer	Mechanical Eng.	X	X		85
Ben Helmandollar	Computer Science			X	64
Avery Holiday	Computer Science			X	64
				Total	2,285

Table 1: Apollo IV Team Distribution

1.2 DESIGN ASSUMPTIONS & DESIGN PROCESS

It was assumed that the design for the 2018 IGVC course would be fairly similar to that of previous years, therefor, the process followed that presumption. The design process for the BSC Robotics Team utilizes a seven-step process as seen in Figure 1. The initial problem presented by the competition is to design and create an autonomous mobile robot that is capable of autonomously traveling to specific way points while navigating an obstacle course. However, because Apollo IV is an upgrade, the design process began immediately following the closing of the previous IGVC by analyzing the performance of the robot and identifying the problems it faced. This was done immediately, in order to identify all fail points, faults, and inefficiencies while they were most apparent. After the extensive analysis of the robot the team assigned priority to each fail point, with innovations with the areas of greatest failures taking the highest priority. Once known, research is done to locate the causes of each problem and find the best solutions. Following the research phase, the team met to present the findings of this research as a group and designs were created for each solution. After design and fabrication was completed the next step was to install modifications to verify a functional system. If adjustments need to be made, the design process is repeated. It is important to note that at all process stages, the team identifies any potential issues to ensure the proficiency of the robot.

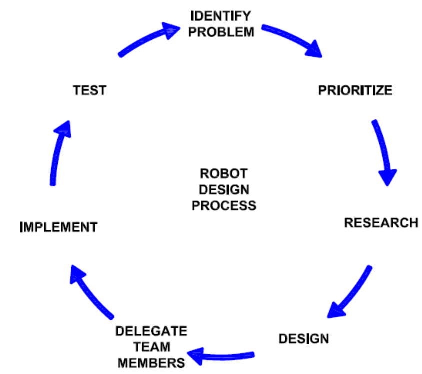

Figure 1: Design Process for Apollo IV

2 EFFECTIVE INNOVATIONS

2.1 Innovative Concepts from Other Vehicles

It was realized that the Basler camera previously used, while operable was not completely adequate for the purposes required. To find a new camera for the Apollo series, the BSC team identified other teams that performed well in the course and performed research on their cameras. It was realized that the SJ 4000 would be adequate for the performance in which was required due to its outdoor ruggedness, cost efficiency, frame-per-seconds needed and wide-angle lens.

2.2 Innovative Technologies Applied

The Apollo series of robots are designed to be completely modular in order to quickly repair or replace any malfunctions or components. During the design process, it was identified that there were numerous issues that could be adjusted and integrted into the Apollo IV system. They are as follows:

- ### Control System

A new micro-controller system that is more modular was designe dinto Apollo IV. The more modular that Apollo becomes, the more scenerios that it will be able to adapt to. The modular micro-controller system allows an alternative between the Parallax micro-controller with 8 cores running different systems and tasks simultaneously or the Raspberry Pi 3 B+. The Raspberry Pi 3 B+ is vertually a mini computer with Linux preinstalled software. Linux based software makes communication with new software systems designed and running on ROS simpler.

- ### 3D Printed Head Systems

In order to integrate the new SJ 400 camera, a new mounting hardware had to be designed because of the drastically difference in shape of the previous barrel camera. The “head” unit is necessary to properly attach the GPS antenna as well as the camera. The square structure of the SJ 4000 presents significantly different mounting conditions as well as changing the air flow conditions thru the head. Solidworks program was used to create the new design that was 3D printed to reduce parts. The square shape of the SJ4000 introduced sharp corners which are significant stress concentration points, therefore, the design was optimized using Finite Element Analysis (FEA) software for Solidworks. The head units were printed and assembled to encapsulate the camera, while still maintaining ease of installation and adjustment of the camera.

- ## Software Modularity

The software systems for Apollo is intended to be as modular as the mechanical or electrical systems. Apollo IV was designed using both LabView and ROS software for different scenarios. LabView is an exceptionally intuitive software for engineers with graphical inputs and outputs similar to a wiring diagram. The use of the Dynamic Link Library(DLL) allows programming in C/C++ which is more efficient for processing time. LabView is designed to use Virtual Instruments (VIs). These small sub programs can be quickly and easily developed or altered in real time. Apollo's software takes advantage of a Global Information Cluster (GIC) which contains all of the robot's data such as software parameters, position information, way points, distances, angles, robot speed, simulations, control commands and angle to way point heading. With this method of software design any number of programmers may develop new VIs and programs independently without being concerned about the specific information stored in each variable as they are universal. Once the system is developed and tested using LabVIEW the programmers can convert the VIs and the code into C/C++ programs with ROS. ROS is much more efficient for use with robotics applications and the use of C/C++ code is much faster as it is much closer to machine code than the more user-friendly language base code found in LabVIEW.

- ## Impact Dampening Gel Shock System

Many of the robots that perform at the IGVC competition have been designed to perform the task of navigation without giving thought to damages to their systems that may be caused by that operation. It has also been the case that Apollo III was functioning very well at the home base course, however, during transit, the camera had been damaged. It is believed that either vibrations from transit or from the rigorous testing may have been the cause. For these reasons, a shock dampening system was developed to extend the lifespan of Apollo. The optimum position for this system was between the mounting hardware of the chassis and the body of the robot. The shock absorbing system was made of a silicone base rubber that was cast into a 3D printed mold. The shape reduces stress concentrations and is hydrophobic, adding to the weather resistance of the robot. The silicone rubber has a very high coefficient of restitution which allows a greater absorption of energy without the energy being transferred to the body of the robot or the sensors and electronics inside.

3 MECHANICAL DESIGN

3.1 Overview

Apollo IV's mechanical design is based on being lightweight, modular, agile, fast and easy to assemble and disassemble. Apollo IV consists of two main integrated mechanical systems: the drive chassis and the body. The drive chassis is a highly modified electric wheelchair chassis which allows for high speeds, zero-degree turns, as well as a very low center of gravity. The body is fabricated from wood and fiberglass and is designed to be light-weight, strong, and weather resistant. Overall, the key components of Apollo IV's mechanical design encompass simplicity with no compromise in performance.

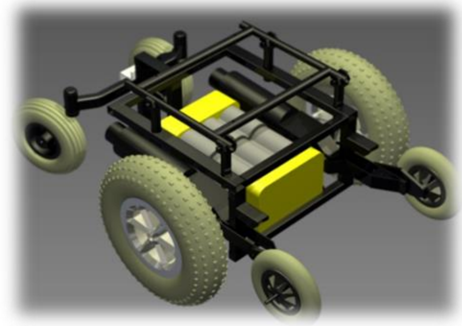

Figure 2: 3D Drawing of Apollo IV's Drive Chassis

3.2 Structure Design

3.2.1 Chassis

Apollo IV's drive chassis, as shown in Figure 2, is developed from a Jazzy electric sports wheelchair chassis. This model was chosen because it allows Apollo IV to achieve speeds exceeding the upper limits of competition without sacrificing maneuverability. The suspension in this model of the Jazzy wheelchair allows for traversal of multiple terrains and environments. The frame has been modified to accommodate a student-designed battery tray, allowing ease of access to the two 12-volt batteries that power the system. The frame has also been modified to accommodate the 20-pound payload easily.

3.2.2 Body

Apollo IV's body is student-designed and fabricated out of wood and fiberglass. Because of this, Apollo is strong and its modularity allows for easy assembly and disassembly. Figure 3 shows Apollo's body during various stages of its development. The curved shape was chosen as it made it safer by not having any sharp corners and was more aesthetically pleasing. The round shape also helps with weather resistance, as water will follow the curvature and run off the robot. Reducing the body weight means reduction of work done by the motors to sustain mobility, which extends battery life allowing Apollo IV to run for hours. The body's top portion can quickly and effortlessly be removed, without tools, providing ease of access to all of Apollo IV's internal components. The body also has a modular design so parts can be added or removed depending on situational demands. The lower mast section and increased mast head has room for additional sensors and equipment. The mast mounting hardware allows for variable masts to be quickly attached and swapped into use.

Figure 3: Top: Apollo IV's Wooden Frame; Bottom: Fiberglass Exterior is Added

3.6 Suspension

Apollo IV is designed to have continuous operation on multiple terrains. Apollo's chassis has a suspension system which was developed to keep the drive wheels in contact with the ground. The extraction of the chair components removed the shock dampening that would have protected the passenger. Without a vibration and shock dampening system, some systems and components of Apollo could be damaged. To reduce the vibrations and impacts to the robot and its sensitive mechanisms, silicone gel shock absorbers were installed. The gel shock was made of a silicone based rubber that is cast into a 3D printed mold. The conical shape reduces stress concentrations from the previous mounting hardware used to attach the body. Because of these corrections, the robot can bounce and absorb the energy of the impacts into the get shock without the energy being transferred to the body of the robot.

3.5 Weather Proofing

It was important that the Apollo IV was designed to operate in various weather conditions. To meet this criterion, Apollo IV's body was designed with a curved shape that causes water to roll off the robot without entering the interior of the robot. This keeps water away from the electrical components that are susceptible to water damage. The body was kept to a minimal number of parts but where there are assembly points, weather stripping was integrated to increase weather proofing.

Apollo IV operates in the sun for extended periods of time, which means it is essential to we keep the internal components cool. Apollo IV's body is designed to meet this goal. The white color and reflective finish redirect heat away from the robot. The fan installed in Apollo also circulates air around the laptop, electrical components, and sensor systems to aid in cooling. The fan also creates a high pressure inside the body of Apollo which pushes air out of the seams where air can escape, which helps with weather proofing by repelling water.

4 ELECTRICAL AND POWER DESIGN

4.1 Overview

The electrical system of Apollo IV has been overhauled completely from the previous rendition of Apollo. In order to make Apollo IV's electrical system more modular, Molex sensor connections and key componenets of the electrical system in the fuse box were installed. This results in a system that can be assembled and disassembled significantly faster. The fuse box was redesidgned and rebuilt with an integrated cooling system to ensure the reduction of overheating components. It was also determined that the DC-DC converter being utilized was transmitting a lower than desired output, therefore, a more accurate DC-DC converted was installed. The electrical system has had a complete overhaul to ensure that all systems in Apollo IV is safer, faster to connect and disconnect, more efficient, and has solid connections with cleaner wires. The original wheelchair control system was previously removed and a completely new design was integrated. The control system consists of an XBee wireless transceiver, Parallax Propeller 8-core microprocessor, and a Sabertooth 2 x 60 motor controller all receiving information from the suite of sensors. Multiple safety features are also an important part of the system. The focus of this design is on safety, reduction of power consumption, fully customizable dynamics control as well as the ability to easily integrate new systems.

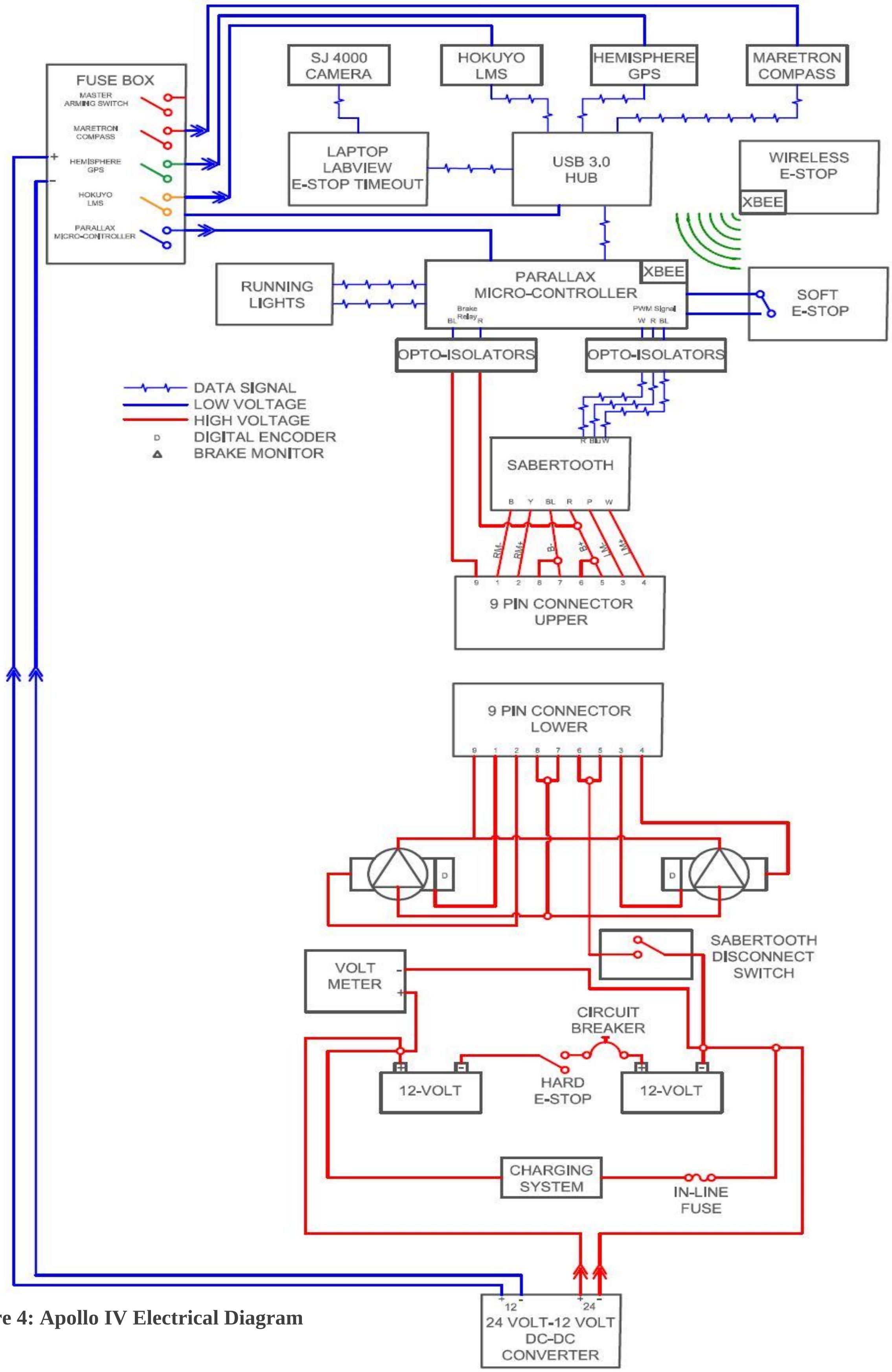

Figure 4: Apollo IV Electrical Diagram

4.2 Power Distribution System

All components in Apollo IV are powered by a single source: two Optima Yellow-Top 12V deep cycle(DC) batteries connected in series to produce 24V DC. The 24VDC power, supplies the motors and brakes through the Sabertooth motor controller, as well as the 24-to-12V DC-to-DC converter, as seen in Figure 4. The 12V DC output of the DC-DC converter supplies power to the fuse box which is distributed to all the other low voltage systems in Apollo IV. Having a single source, coupled with a smart charger, makes charging Apollo IV simple and intuitive. The fuse box with integrated color-coded switches for all sensors and devices also aids in power savings. Only sensors being used during testing are turned on, allowing for quick disconnecting/connecting during testing. The motor controller employs synchronous regenerative braking to recapture energy during downhill descents and braking and reduces heat.

4.3 Control System

As mentioned in the Mechanical Design section, Apollo's chassis was originally an electric wheelchair. As such, the original control system was the wheelchair controller- complete with its own joystick and other components. The control system was previously replaced by a system entirely developed by BSC Robotics students. The new control system was designed around the Parallax Propeller 8-core microprocessor coupled with a Sabertooth Motor controller. Extra consideration was put into transient suppression and electrical isolation of parts to prevent future component failure. Opto-isolators were used between the motor controller and microprocessor to physically separate the two assemblies since they operate on different levels of voltages and currents. A ferrite core toroid on the motor wiring harness reduces transients from reverse voltage of the motors. The brake relay uses a flyback diode for transient suppression, a capacitor to reduce arcing, and an opto-isolator ensures operation of the brakes while keeping the higher voltage isolated from the microprocessor. The control system is depicted in Figure 4. The system now incorporates the ability to change between the Parallax micro-controller and the Raspberry Pi 3B+.

4.4 Sensor Systems

Apollo IV uses four sensors: an LMS, a camera, a GPS receiver, and a compass. These sensors are used to collect information from the outside world, and were chosen by the team for their proven accuracy and speed- perfect for performing at IGVC. These sensors are described below:

- **<u>Camera</u>**: An SJ4000 action camera, as shown in Figure 5, has been selected for multiple reasons. With a frame rate of 30 frames per second and high-speed data transfer, this camera synchronizes more efficiently with the other systems for accurate path planning in software. Additionally, automatic white balancing, gain adjustment, and shutter speed control allow for excellent vision in any lighting condition. The camera also features auto focus and auto light adjustment.

Figure 5: Camera

- **<u>Laser Measurement System (LMS)</u>**: Apollo IV uses a Hokuyo LMS, seen in Figure 6, for object detection. With a 270-degree field-of-view at 0.25-degree increments and a detection range of up to 30 meters, the LMS provides extremely accurate object detection. It cycles at 40 Hz, allowing ample time for Apollo IV to detect any obstacles in its path. The LMS also features data clustering, specular measurement, and adjustable resolution levels for maximum customization.
- **<u>GPS</u>**: To obtain positioning data, Apollo IV uses a Hemisphere GPS and the A21 antenna (L1, GNSS, L-Brand) from Blueplanet Geomatics shown in Figure 7. This provides position, direction, and speed data, allowing Apollo IV to track both its own position and those of user-defined waypoints. The GPS antenna and the A21 antenna used for differential corrections are housed in the same location. This GPS unit runs at 20 Hz, making it easy for Apollo IV to navigate through the course at high speed.
- **<u>Compass</u>**: A Maretron Solid State Compass, shown in Figure 8, assists in determining vehicle heading. Since the heading data provided by a GPS unit is less accurate when the vehicle is stationary or moving at low speeds, it is supplemented with the compass. It provides an accuracy of 0.1 degrees, and updates at 100 Hz to verify the direction. The Maretron compass is designed to function with pitch and roll up to 45 degrees, preserving its functionality on inclines.

Figure 6:LMS

Figure 7: Hemisphere GPS

Figure 8: Maretron Solid State Compass

4.5 Safety Devices and Systems

Apollo IV has many safety features. Four independent systems have been employed to stop the robot quickly. There are two physical switches integrated into the body of the robot itself: the soft E-stop gives the processor a software pause command and the hard E-stop physically cuts power to all systems as seen in Figure 4. A wireless E-stop sends stop commands well exceeding the minimum requirement of 100 feet for IGVC. There is also a firmware timeout implemented, should the Sabertooth fail to receive a valid signal within 100 milliseconds that will stop the robot. Another safety feature the Sabertooth provides is the ability to limit the maximum speed. A separate brake/motor monitor circuit has also been added to Apollo IV. Anytime the brakes and motors are not synchronized properly, the multi-core Propeller microcontroller will command the robot to stop. This system is particularly effective since the brake/motor monitor is controlled by an independent core of the Propeller processor.

5 SOFTWARE STRATEGY AND DESIGN

5.1 Overview

Apollo IV's software is developed using LabVIEW. Using LabVIEW allows Apollo's users to easily create a sophisticated graphical user interface that makes it simple for them to monitor data, change settings, and debug the software. LabVIEW also has a visual programming environment that is very familiar to the electrical team members, which allows more of the team to be able to write code. Apollo IV's path planning algorithm revolves around mapping sensor data to an 80 x 80 2D grid of weighted nodes that represent the area around the vehicle. The LMS locates obstacles, and the vision system detects lines. These sensors send their information to an onboard laptop which maps the data to the grid of nodes mentioned above. Location and heading information received from the GPS and compass are used, in combination with the obstacle data in the grid, to select a goal on the map that will progress the robot to the next waypoint while still avoiding obstacles. The path planner is then used to create a safe path from the robot to the goal using a weighted shortest cost path equation. The last step is to smooth out the path, which determines the commanded heading and speed of the robot.

5.2 Obstacle Detection and Avoidance

Apollo detects objects with its laser measurement system. The LMS provides an array of distances to objects detected within a 270º arc centered directly in front of the robot. Apollo also uses a camera to detect white lines on the ground. Image processing reduces the camera input to a 360 X 480 bitmap consisting of ones and zeros.

5.3 Software Strategy and Path Planning

Apollo's earlier pathfinding algorithms used an 80 x 80 2D array of weighted nodes. Various algorithms were employed to implement this system, but all were susceptible to cycles due to the possibility of the algorithm being presented with the same data and making the same decision in a never-ending loop. Pathfinding algorithms, such as Dijkstra's algorithm, A*, and Jump Point Search rely on a complete map to find an optimal path. Since Apollo does not have access to a complete map of its surroundings, a new algorithm is being developed to find a path when unknown nodes exist between Apollo and its destination.

5.4 Map Generation

The 80 x 80 map in previous generations of Apollo was discarded on every cycle leaving the pathfinding algorithm to choose a path based solely on the most recent batch of data reported from its instrumentation. A new global mapping system is being written to store persistent data on a much larger (2048 x 2048 or even larger) two-dimensional array of nodes. These nodes indicate obstacles and contain variables recording the distance at which they were detected by the camera or LMS. In this way, information mapped at long distance is replaced by more reliable data obtained at closer proximity. Nodes mapped at close distance won't be overwritten by data obtained from far away.

5.5 Goal Selection and Path Generation

The new pathfinding algorithm looks for the current waypoint on the map. Like A*, it uses a priority queue to attempt to quickly find the optimal path without evaluating un-necessary nodes. However, if the current waypoint is not on the map, Apollo must cross unmapped nodes to reach the waypoint. The new algorithm finds nodes adjacent to un-mapped nodes during its search for the waypoint. It evaluates each of these special nodes and stores the most attractive node based on the heuristic assigned to that node and distance from the robot. If the waypoint is not found, the priority queue will be completely analyzed leaving Apollo with a destination adjacent to an unexplored area. If the way-point is located, the waypoint node will become the destination. As the pathfinding algorithm traverses the map, it assigns each node with a parent node. This provides Apollo with a path back to the robot from the destination. A simple linked list traversal back-wards through the path to Apollo yields a path of nodes which can then be smoothed to generate a direction and speed. These values are converted to PWM's to be sent to the motor controllers.

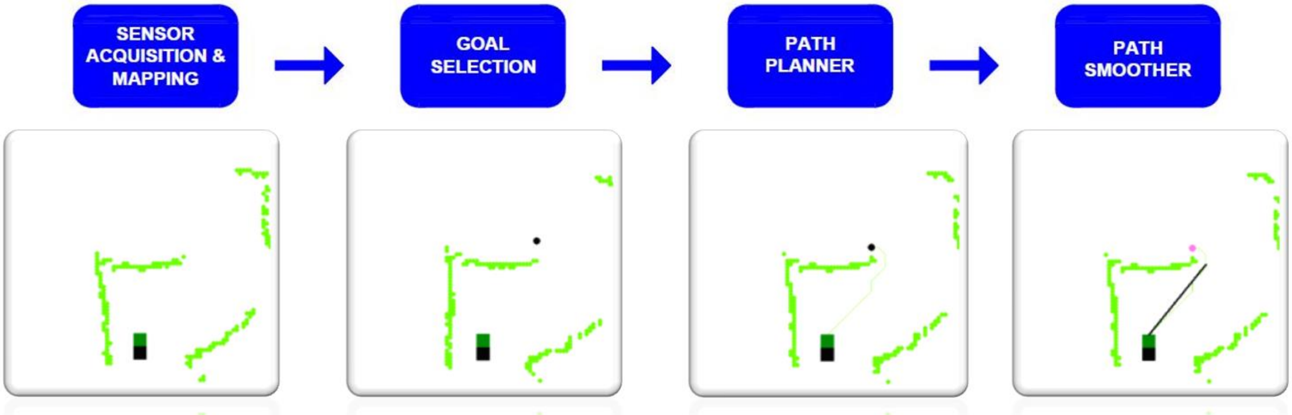

Figure 9: Apollo IV Navigation Strategy

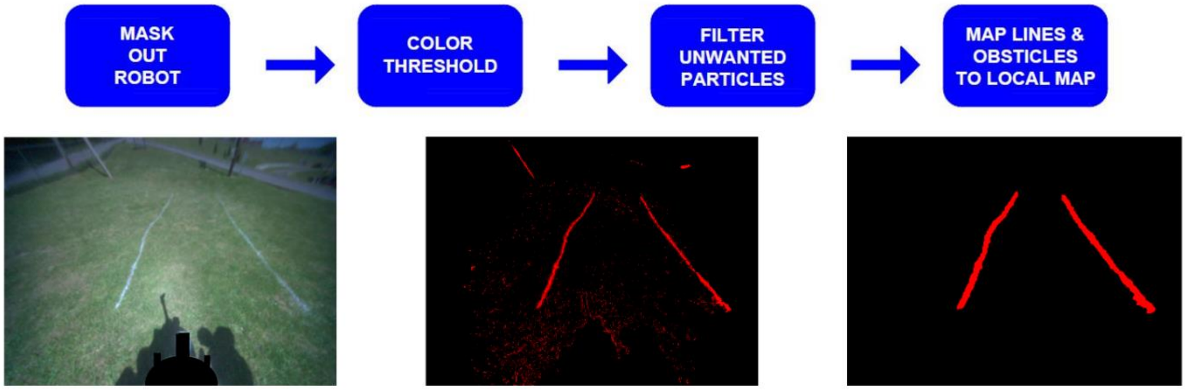

Figure 10: Apollo IV Line Detection Strategy

5.6 Additional Creative Concepts:

Knight-Star is a truly unique method for pathfinding in unknown areas. Past softwares were efficient at finding the most direct path to a way point with known obstacles. If an area is unknown or unexplored, Knight-Star is highly efficient at finding the most operable path to the way-point. software is a unique software designed for unknown areas and developing

6 FAILURE: MODES, POINTS, AND RESOLUTIONS

6.1 Vehicle Failure Modes and Resolutions/Strategies

- Failure: Apollo III sometimes experienced ineffective navigational choices due to logic errors
  Resolution/Strategy: Added global mapping software. Improved navigation algorithm. Synchronized sensor data to have more accurate variables in global information cluster.
- Failure: Basler Camera operating at 90 frames per second, with vision processing per every frame, was significantly greater than necessary
  Resolution/Strategy: switch cameras to a camera that is more in sync with the needs with software strategy, speed and processing time

6.2 Vehicle Failure Points and Resolutions/Strategies

- Failure: Camera sustained physical damage during testing or transportation to competition due to vibrations
  Resolution/Strategy: Incorporate shock absorption into Apollo IV
- Failure: Stress cracks in body of Apollo
  Resolution/Strategy: Incorporate shock absorption into Apollo IV
- Failure: Imbalanced center of gravity
  Resolution/Strategy: Re-manufacture lower mast section
- Failure: Voltage drain/switches overheating
  Resolution/Strategy: fabricate new fuse box eliminating loose connections

6.3 All Failure Prevention Strategy

Apollo is designed as a fully modular robotic system, with the ability to adapt to various situations quickly using both physical modularity and software modularity.

6.4 Testing

In testing Apollo and its systems, we use extensive LabVIEW simulation as well as rigorous testing on student created physical course to identify failure modes and points.

6.5 Vehicle Safety and Design Concepts

Safety is incorporated into the design of Apollo in all areas. The electrical system incorporates multiple safety features as seen in figure 10 above. The body of Apollo is designed with no sharp corners to prevent injury. The software system of Apollo increases the area around all detected objects to adjust for inaccuracies of the sensors.

7 SIMULATIONS

Apollo IV has a simulation program, displayed in Figure X, that allows for the creation of a personalized courses and test how Apollo IV's software reacts to different situations. The Robotics Team has created several different courses to test Apollo IV's software on. This has proved to be invaluable to the software development. It is much easier and faster to create a virtual course than to create a real course. The simulations were critical to the development of Apollo IV during the vehicle's downtime while its' mast platform was being re-manufactured. Figure 11 shows the simulation running on user generated course. The blue triangle at the top is Apollo's current position while the blue line is the path Apollo has taken. Black circles are waypoints and red objects are obstacles.

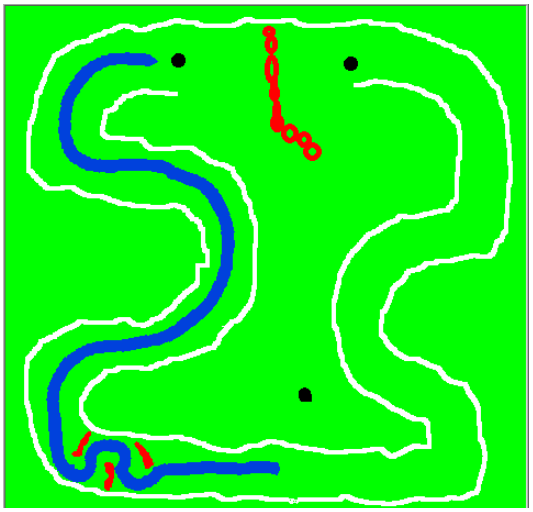

Figure 11: Apollo IV simulation running

8 PERFORMANCE TESTING AND ASSESSMENT

Table 3: Testing and Assessment

Category	**Analysis Method**	**Predicted Performance**
Speed	Tested	5 MPH
Ramp climbing ability	Tested	30% slope
Reaction time	Limited by software cycle time	25 ms
Battery life	Calculated	2.75 to 5.5 hours (depending on usage)
Distance at which obstacles are detected	Hokuyo spec is 30 meters. Restricted by software.	7 meters
Accuracy of arrival at navigation waypoints	Hemisphere specs and tested	2 ft. 67% of the time

Apollo IV's estimated average current draw for normal operation is between 10-20 amperes depending on usage. The batteries are rated at 55 amp-hours, therefore the estimated battery life is 2.75 to 5.5 hours, as calculated by the equation below. Run time is measured in hours, battery energy in amp-hours, and average current draw in amperes.

$$Run\ Time = \frac{Battery\ Energy}{Average\ Current\ Draw} \rightarrow \frac{55}{10} = 5.5 \text{ hours}$$

9 INITIAL PERFORMANCE ASSESSMENTS

The initial performance of Apollo IV has shown that the robot performed satisfactorily using the improved control system and mechanical systems. The autonomous function performed to date and continues to improve as fine tuning of software continues as the competition draws near.