APOLLO IGVC 2015

1. INTRODUCTION

Nestled in the Appalachian Mountains, Bluefield State College is a close-knit community of people driven to make a positive, significant impact on the world by empowering others through affordable education. Based on our years of consistent excellence in robotics, Bluefield State's Robotics Program plays a key role in the global recognition that Bluefield State has today. This year, BSC Robotics would like to proudly introduce to you our new autonomous robot, APOLLO. The unique design and sophisticated look of APOLLO will be an innovative game changer. Many of our design features have never been seen in any vehicle at IGVC. These innovations include parallelism, ability to operate in severe weather conditions, and modularity. In addition to APOLLO's incredible torque, speed, precision, and accuracy, these innovations will raise the bar in the ever-dynamic world of intelligent ground vehicles. Figure 1.1 shows our show-ready product, APOLLO, on the course during testing.

Figure 1.1: APOLLO During Testing

2. DESIGN TEAM/PROCESS

2.1 Design Team

Our team, which is comprised of undergraduate students in engineering technology and computer science, focuses on integrating electrical, mechanical, and computer engineering skills into our design. Our team was carefully selected based on our need and their area of study and expertise. As Table 2.1 shows, the team is very diverse in its abilities, covering all anticipated aspects of Apollo's design. Two outstanding faculty members, Dr. Robert Riggins and Dr. Adem Ozyavas, from the Electrical Engineering and Computer Science departments provide guidance to our team. Our committed team of members has collectively devoted over 1500 hours to this project this academic year. Most members of the team have also received instructional credit of up to 5 hours on topics in robotics. The APOLLO robotics team was responsible for all aspects of the design, simulation, fabrication, and testing of BSC's 2015 IGVC robot. Figure 2.1 shows the 2014/2015 APOLLO's robotics team. The APOLLO team is listed in Table 2.1: APOLLO Team, below.

Figure 2.1 BSC's Robotics Team, IGVC 2014/2015

Team Member	Department and Year	Design Task(s)
Alex Enoch (Team Captain)	Electrical Engineering Senior	Design Coordinator, Team Leader
Levi Poff	Computer Science Junior	Software, Sensors, Communications
Andrew Smith	Computer Science Senior	Software
Feyijimi Adegbohun	Electrical Engineering Senior	Electrical Design/Public Relations
Lawrence Bane	Mechanical/Electrical Senior	Electrical/Mechanical Design
Corey Nunn	Electrical Engineering Senior	Electrical
Brandon Tolley	Mechanical/Electrical Senior	Electrical/Mechanical/ CAD
Doug Reynolds	Computer Science Senior	Designer and Fabricator of Body
Seth Weakley	Electrical Engineering Senior	Electrical Design
Greg Hogan	M.E. Sophomore	Fabrication
Michael Goforth	M.E. Sophomore	Mast design, Fabrication
William Lambert	M.E. Sophomore	Fabrication
Nathan Taylor	M.E. Sophomore	Fabrication
Hollie Fuller	Business & I.T. Senior	Marketing and Software

Table 2.1: APOLLO Team Members

2.2 Design Process

After carefully choosing our diverse team, we then established the game plan for building an optimal autonomous intelligent vehicle that would compete at the 2015 IGVC. Our design process focused on a number of innovative concepts that could potentially raise the bar in the design of intelligent vehicles by meeting and exceeding the expectations and specifications at the IGVC. The innovations listed in the following section formed the foundation by which the team designed APOLLO.

The second part of our design process involved dividing our team into sub-teams based on area of specialization. The focus of each sub-team was on integrating all the innovations we agreed to incorporate into APOLLO's design. Our team leader was chosen based on his broad knowledge and expertise of all aspects of the design, both hardware and software as well as his avid knowledge of the IGVC requirements and rules.

After weeks of brainstorming, planning, designing and presenting of prototypes and design proposals, each sub-team began fabrication of hardware and software design. Figure 2.2, below, shows the progression in the construction of APOLLO from start to finish.

Figure 2.2: APOLLO Construction Stages

3. DESIGN INNOVATION

3.1 Overview

APOLLO's design this year has been carefully tailored to produce an optimal robot that will exceed the expectations of our opponents and judges. Our intelligent vehicle's design has innovations in both hardware and software. Advanced software communication techniques and sophisticated mechanical strategies are implemented to make APOLLO one of a kind.

3.2 Hardware Innovations

Speed

The team agreed that one of our primary innovations was to build a vehicle that could actually achieve IGVC's maximum speed requirement of 5mph. Having noticed at previous IGVC's that all robots are much slower than the maximum speed allowed, we decided to make speed and accuracy our top innovation this year. APOLLO can go as fast as 5mph through the course. To achieve this innovation we have significantly improved the speed and accuracy of data processing from our top-of-the-line sensors as described in later sections.

Modularity

A key hardware innovation on APOLLO is the fact that it can be taken apart and put back together in a matter of minutes. With a detachable mast, body cover, instrument tray, underbody, and frame, APOLLO's modularity makes repairs and modifications easy. Each of its parts can be taken apart and put together very quickly.

Composite Body

Going from an aluminum body style to our incredibly unique fiberglass body style has made APOLLO even faster and easier to maneuver on the course than previous robots allowing for greater precision and accuracy. The curved rounded shape is much safer than shapes with edges, and also creates maximum room inside for all of its components. This body style has also increased our ramp climbing abilities. APOLLO can climb a ramp inclined at over 30 degrees, at full speed (5 miles/hour), with a full payload. In addition, APOLLO's stylish look makes it stand out. APOLLO is finished sophisticatedly to look like an actual vehicle that can be sold in an intelligent autonomous vehicle lot. The body is finished with automobile paint and detailed curves to give it a sleek look

Ability to Operate in Severe Weather

APOLLO is also designed to perform at maximum efficiency completely regardless of the weather. The body is designed like a capsule with no flat surface, which causes rain to easily run off the body and conceals all of its electrical components and sensors. This protective capsule effect of APOLLO's body is further reinforced by the use of gasket materials in between cracks and doors, as used in automobiles. Positive pressure from our integrated cooling system provides a further deterrent to water entry.

LED Indicators

APOLLO is equipped with LED lights that indicate its various functions. Different colors and shades of lights indicate what sensors are being used and what functions each of the sensors are actually performing on the robot. This is a very useful tool in troubleshooting, and enhances the user-friendliness in controlling APOLLO. These LED indicators are all programmed and controlled by the propeller microprocessor on APOLLO.

Servo Rotating Mast design

Rather than keep the camera in one spot and angle above the robot, our innovative design can move the camera about the robot. We designed the mast with a 2-foot horizontal extension and a servo at the base to "swivel" the mast. This gives APOLLO the ability to move its camera in a semi-circle of radius 2 feet, allowing it to see clearly along this arc. This mast design gives APOLLO the ability to see on the other side of obstacles such as a barrel.

3.3 Software Innovations

Parallelism

The introduction of parallelism into our design was a major milestone in the design of APOLLO. After extensive research and testing in LabVIEW 2014, we were able to implement parallelism in our design and collect data from all the different sensors on APOLLO. The LabVIEW 2014 software gave us the ability to use all eight cores of our processor through parallelism. We were able to integrate the data received from our sensors into APOLLO's control and response, all at the same instance in time. APOLLO now uses a process similar to the human brain. Each sensor updates a group of shared variables. These variables provide a constantly changing informational environment. All sensors now provide information at their hardware-limited speeds. Path planning monitors data for a change, plans a path, and then resumes monitoring. Using this information set, the path planning process is able to react to any data change as soon as it occurs. This achievement not only made APOLLO's controls much more precise and accurate, but also takes away limitations resulting from dissimilar sensor speeds.

Communication System

Alongside APOLLO's extensive local communication system, APOLLO now boasts a new wireless communication system. Taking advantage of LabVIEW's shared variable technology allows us to easily and efficiently share data across our wireless LAN, as generated by an on-board router. This gives our team members great flexibility, as any WiFi enabled device can connect to our network and monitor data, modify variables, and even E-stop the vehicle. This allows multiple team members to monitor and control APOLLO from a distance, improving our debugging capabilities and safety.

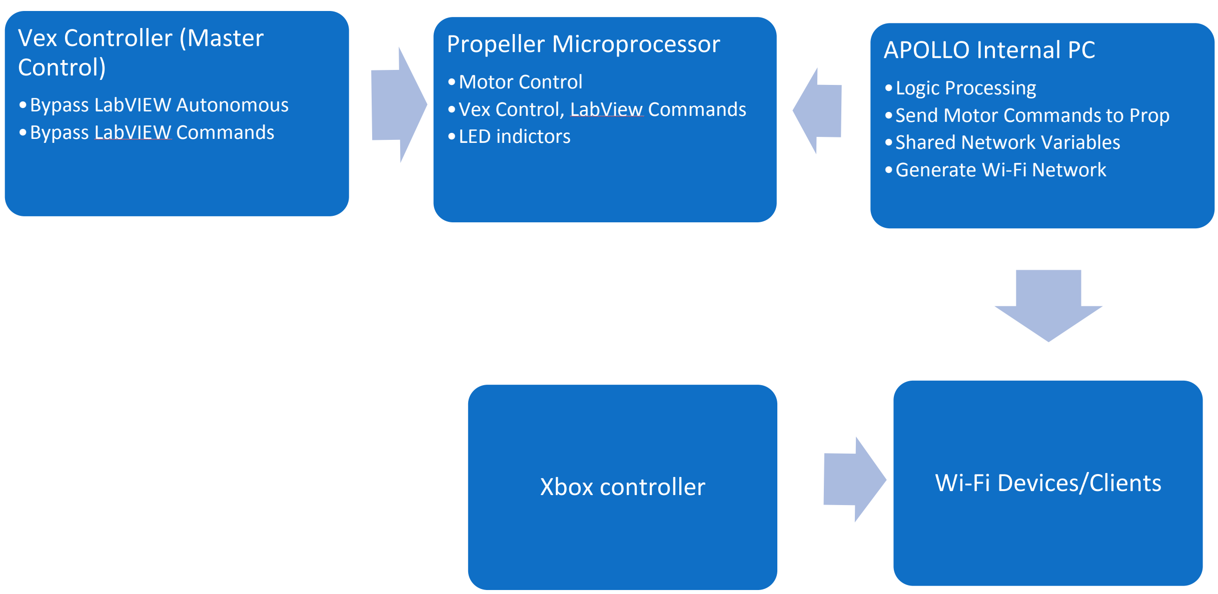

Figure 3.1 APOLLO Communication System and GUI

Vision Pipelining

Our sensory capabilities have increased tremendously with the addition of our high frame rate, high data-transfer speed camera. Our software has equally improved with the use of the modular development design platform of LabVIEW 2014, giving us the ability to exploit parallelism. One of the possibilities that parallelism has added to our innovation is vision pipelining. Vision pipelining enables us to save images in our RAM while enabling us to process each image in image in a pipeline format. This means that processes start before the entire set of processing is finished, providing us with an even faster frame rate. Nearly infinite images can be stored in the RAM, so we have five frame buffers set up. This eliminates any potential decrease in frame rate speed that could occur when the camera vision transitions from light to dark or vice versa. The frame buffer picks up the slack during this transition, so the camera always stays ahead, even when the frame rate slows down for a millisecond. Three different parallel pipeline processes function seamlessly in APOLLO's vision program for white objects, red objects and blue objects. Figure 3.2 shows a conceptual image of our vision-pipelined process. This unique feature is a definite game changer that will enable our robot to perform with higher accuracy and precision.

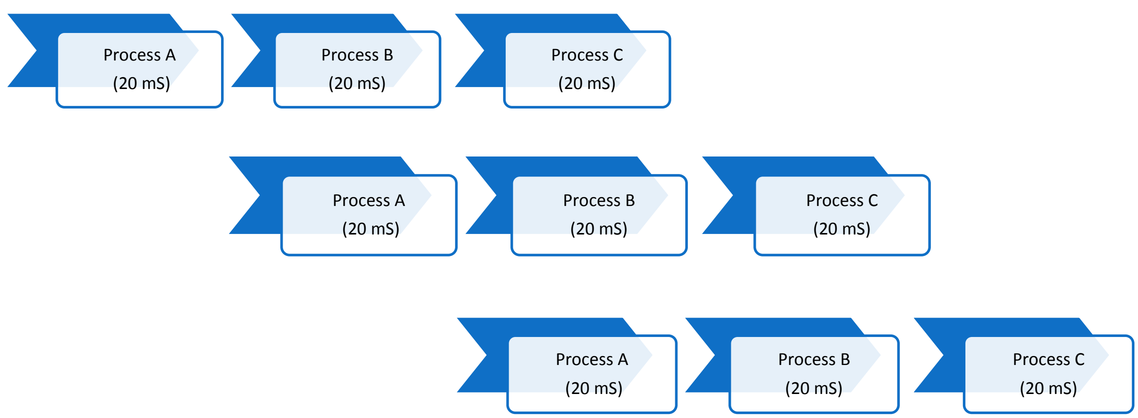

Figure 3.2 Pipelined Vision process

4. MECHANICAL DESIGN

4.1 Overview

At the 2014 IGVC competition, all of our team members were new to IGVC, and our team was all but attacked by a swarm of curve balls. However, with diligence, tenacity, and sheer grit, we found solutions as each curve ball manifested. Not only did we qualify, we also ran an outstanding 120ft. During the competition, we discovered that we had a simple but undeniable design flaw with our vision on ARES, our 2014 IGVC robot. We had erased ARES from a certain part of the map and the position of the mast for the camera obscured a critical area of our vision. This could never work since it made us blind to white lines in certain places. Even though we found this important design flaw to be very disappointing, we gained an invaluable, solid foundation of experience that catalyzed our many improvements during the design, construction, and various sub-designs of APOLLO. Now, APOLLO's entire mechanical design was created based on this experience that our whole team shares from last summer, and our intention is to make APOLLO mechanically flawless over time.

4.2 Drive Frame

One of our innovations listed in the previous section is to increase the speed of APOLLO, even during maneuvers, up to the maximum limit of 5mph. In order to do so we have to ensure the mechanical design can handle this. APOLLO features a base constructed using the frame, motors, and motor controller from an 1170 Jazzy electric sports wheelchair base. We chose the sports base because it is designed for higher speeds than most wheelchair bases. The wheels are designed with ruggedness and rigidity features to fit any terrain and environment. Upon this frame sits the holding slots, designed and fabricated by our robotics team for our two 12 volt batteries. The frame also houses our drive motors, DC-to-DC converter, as well as our payload slot. Figure 4.1, to the left, shows a detailed AutoCAD rendered drawing of the wheel frame of APOLLO. We kept the original anti-tilt wheels and swivel wheels to ensure APOLLO exceeds the IGVC requirements of ramp climbing and maneuvering around the course.

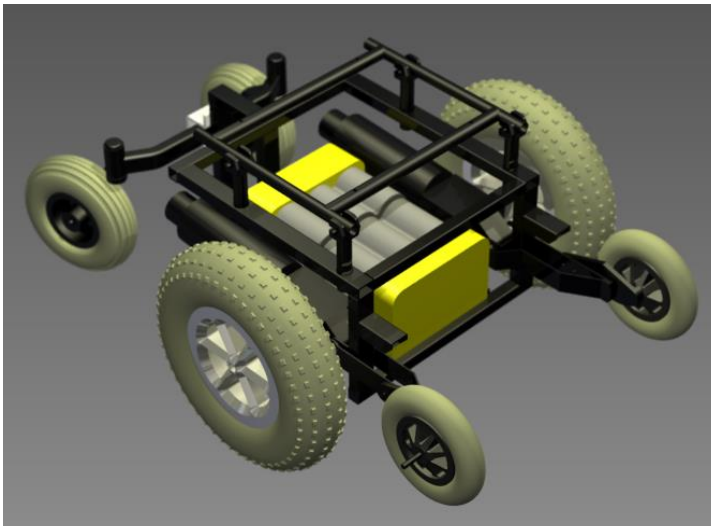

Figure 4.1 APOLLO Drive Frame

4.3 Mast Design

Figure 4.2 APOLLO Mast

The design of our Vision mast was specifically tailored to fit the simplicity of our vision strategy and the overall sophisticated appearance of our intelligent vehicle. The mast is comprised of a small PVC pipe faced down with our camera inside of it, and the camera points straight down. This design enables our intelligent vehicle to see everything around the base of our robot at a higher frame rate. Our design also features modularity, allowing the camera mount can be taken off and readily remounted for ease of maintenance and transportation. Figure 4.2 is a picture of the modular mast carrying the camera of APOLLO.

4.4 Cooling Unit

During the design of APOLLO, we realized that a lot of heat was being generated in the computer unit and some of the other components of the APOLLO such as the GPS receiver and compass. In order to solve this problem, we installed a cooling unit inside APOLLO that cooled down the heat generated in the processor. The fan sits below the deck where all the electrical components are, sucks air from below the robot, blows it through the mast, and out of the camera compartment.

4.5 Specifications

APOLLO is designed to meet IGVC specifications and requirements. APOLLO is 180.3 centimeters in height, and 65.52 centimeters wide, and 167.6 centimeters long. It weighs about 115 kilograms, including the 9.1 kilogram payload when fully loaded. It has a solid framework and a completely weather-proof exterior for optimal performance come rain or shine. This base has been modified to allow the top of APOLLO to be removed by pulling four pins, then simply lifting the top portion off. It has ample internal space for components, easy access doors, a convenient control panel for operation, and a sleek look. Atop the main portion of the APOLLO body sits a mast, which houses the GPS receiver, camera, and running lights. The connectivity of these three main components allows for portability, serviceability, and versatility.

Detailed Specs

- Top Speed: 5mph
- Ramp climbing ability: 30 degree incline
- Reaction times: as low as 12ms
- Battery life: minimum of 30 amp-hours; 1 hour at full speed
- Distance at which obstacles are detected: 30 meters maximum
- Accuracy of arrival at navigation waypoints: 0.6 meter

5. ELECTRICAL DESIGN

5.1 Overview

We designed the electrical component of APOLLO in such a way to incorporate our innovations stated earlier into the design. For example higher speeds require extra safety precautions and an ample power source. Extreme weather capabilities require adequate electrical protection and housing. Cooling of electrical components that generate heat is extremely important as well. Modularity of our design also allowed our electrical systems to be easily accessible for maintenance as well.

5.2 Power

APOLLO's power system is specifically designed to distribute power to all the different components and parts of APOLLO from a single source. APOLLO's only power source consists of two Optima Yellow Top 12 Volt-DC deep cycle marine batteries, rated for 30 amp-hours each. The location of these batteries near the bottom of APOLLO's frame helps to provide a low center of gravity, which allows for greater ramp climbing ability. Following our design concept of modularity, the batteries slide out on a tray for access and/or replacement. The batteries will power APOLLO's systems, under normal conditions, for nearly an hour at full speed, and much longer at slower speeds. This 24-volt power system runs two motors, a wheelchair controller or a sabertooth motor controller, and a 24-to-12 Volt DC-DC converter. All devices get their power from these batteries and the majority of the devices and parts on APOLLO are powered through the DC-DC converter through a central fuse box.

5.3 Safety Devices

To ensure safety, all devices are separately fused, providing over-current and ground fault protection. Each internal system has its own casement, which further reduces possibility of electrical damage or ground fault. The design of the body of APOLLO also enhances durability by providing shock absorption and shielding for the internal components against electrostatic discharge. With its completely nonconductive, waterproof fiberglass body, APOLLO has yet another layer of electrical isolation, which none of its predecessors enjoyed. All this contributes to the ruggedness of APOLLO, allowing us to achieve our speed innovation.

APOLLO features four independent hardware emergency stop (E-stop) mechanisms. The first is a direct "kill switch" which disconnects the power to all sections of the APOLLO's system. The second is a wireless, hard-wired version of the same device, allowing remote emergency shutdown. Third, APOLLO contains what we refer to as the "soft E-stop," a system that shuts down power to the motor controller while leaving other systems powered. The soft E-stop button sits right on the motor controller of APOLLO. Finally, a toggle switch, in parallel with a magnetic relay, removes the computer control from the APOLLO system, allowing a user to take manual control of the robot using a backup wired joystick. This joystick hardwired to the motor controller is a very important precaution device because if all other forms of control fail, the robot vehicle can still be controlled with this device. It can also be activated from a convenient button on the remote control device, allowing the team to instantly take control of APOLLO under any circumstance.

5.4 Control System

Propeller Microcontroller

To provide an interface between the laptop and the microcontroller, we designed a custom micro-controller board using a Parallax 8-core propeller processor. Not only does our board provide motor/brake commands to the motor controller, it also controls wireless manual operation, provides feedback information, and controls all indicator lights on APOLLO. The ability of the propeller microcontroller to communicate via lights meets one of our hardware innovations mentioned earlier.

Motor Controller

The propeller microcontroller provides commands to APOLLO's motor controller, which can be either a wheelchair controller, or a sabertooth controller. Both these controllers have safety built-in by protecting the motors from transient reverse voltages. The wheelchair controller requires some alterations whereas the sabertooth controller requires no changes. Apollo can operate with either; however, for testing we are currently using the wheelchair motor controller. A diagram of our control system is shown below in Figure 5.1

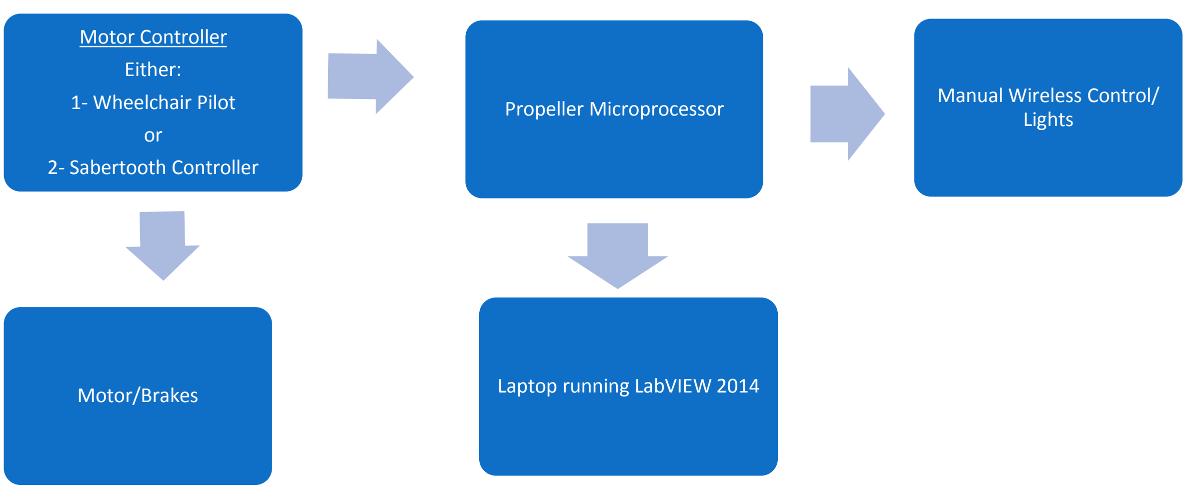

Figure 5.1: APOLLO Control System

6. SENSOR SYSTEMS

6.1 Overview

In order to make APOLLO the fastest and best performer on the IGVC course, we knew we had to have top-of-the-line sensors. The sensor suite on APOLLO is hand-picked by the team, and all sensors are fast and accurate. APOLLO uses four sensors to interpret information from the outside world: a Global Positioning System (GPS), a Laser Measurement System (LMS), a camera, and a digital compass. Each sensor is mounted so that it can easily be removed and remounted in order to meet our modularity innovation. All of these sensors connect to our on-board laptop using USB, making them easy to connect and disconnect. With a fused USB hub, the laptop is isolated from any electrostatic discharge or power surge that might travel through the USB data connections. A brief description of each sensor follows.

6.2 Camera

A Basler USB 3.0 outdoor camera has been selected for multiple reasons. With a frame rate exceeding 100 FPS and high-speed data transfer, this camera provides more than enough speed for all of our needs. Additionally, automatic white balancing, gain adjustment, and shutter speed control allow for excellent vision in any lighting condition. When combined with a horizontal 125-degree field-of-view lens that has merely 3% distortion, the APOLLO vision system has exceptional precision and versatility.

6.3 Laser Rangefinder

APOLLO uses a Hokuyo LMS scanner 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 to detect any obstacles in its path. The Hokuyo also features data clustering, specularity measurement, and adjustable resolution levels for maximum customization.

6.4 GPS & Antenna

To obtain positioning data, APOLLO uses a Hemisphere GPS, the A21 Antenna (L1, GNSS, L-Band) from Blueplanet Geomatics. This provides position, direction, and speed data, allowing APOLLO to track both its own position and those of user-defined way-points. The GPS antenna and the A21 antenna used for differential corrections are housed in the same location. This GPS unit runs at a speed of 20 Hz, making it easy for APOLLO to navigate through the course at high speed.

6.5 Compass

A Maretron Solid State Compass assists in determining vehicle heading. Since the heading data provided by a GPS unit is less than reliable when the vehicle is still or moving at low speeds, it is supplemented with this compass. It provides an accuracy of 0.1 degrees, and updates at 100 Hz to verify our direction. The Maretron compass is designed to function with pitch and roll of up to 45 degrees, preserving its functionality on inclines.

7. NAVIGATION

7.1 Overview

As with hardware design, our software design also focused on innovations listed earlier, including parallelism, vision pipelining, and our wireless communication network. In this section, software strategy, including software development, signal processing, system integration, map generation and goal selection will be discussed.

7.2 Basic Strategy

The APOLLO navigation software gathers sensor information, fuses this information together, generates a local map, selects a goal, plans a path, and makes control decisions. Path planning takes place approximately every 15 milliseconds. Due to parallelism, each sensor updates a bank of data at maximum speed regardless of other events.

7.3 System Integration and Signal Processing

Sensor information from our four sensors, a Hokuyo LMS, a Basler camera, a Hemisphere GPS, and a Maertron magnetic compass, are all integrated into a single data bank, which eventually becomes our local map. LMS data is weighted to highest priority, since it is the most accurate of the sensors. The image is split into three copies, each of which is processed in parallel with the others. Red, blue and white are extracted, filtered for interference, and reduced to a size appropriate for the map. White is passed through an additional filter set designed to reduce glare. The red and blue areas are checked for size to confirm that they are flags, not barrels. Areas to the appropriate sides of flags are also marked to ensure passing on the correct side. All three colors are assigned values, and then added to the local map. The GPS and magnetic compass data is used for APOLLO position and heading, and also used in the goal selection stage of processing.

7.4 Map Generation

The APOLLO local map is composed of 6400 cells making an 80x80 grid, which represents an 8x8 meter area, with each cell representing 0.1 meter by 0.1 meter. The upper left and lower right cells have a location of (0, 0) and (79, 79) respectively. APOLLO occupies cell (60, 40). This gives APOLLO a forward range of 6 meters, a sideways range of 4 meters, and a rear range of 2 meters upon which to plot its map. During map generation, each open cell is assigned a value of 1000. This allows us to modify this value to represent locations to which APOLLO does or does not want to travel.

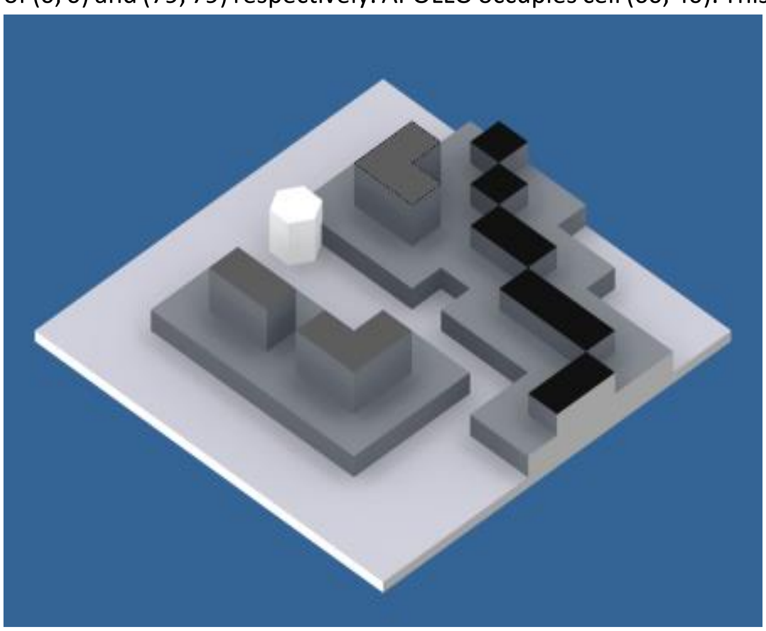
Figure 6.1 APOLLO local map with "fat" layer added

Sensor data is added to this map as it becomes available using the technique described above. Adding a layer of what we call "fat" around objects creating a buffer zone to ensure that APOLLO does not collide with objects. It is adjustable to allow for fine-tuning of the map, and normally it provides a buffer of 0.4 meters to either side of an object. With APOLLO's width being 0.66 meters, this should provide APOLLO with a clearance of 0.07 meters on either side in all scenarios. Figure 6.1, on the previous page, shows a conceptual drawing representing obstacles with "fat" added. The white hexagonal shaped element in the figure represents APOLLO.

7.5 Goal Selection and Path Creation

Since APOLLO uses a local map that is much too small to encompass the entire course, provisional goals must be selected within the boundary of APOLLO's maps. These goals are selected through a dynamic weighted equation (see below) using five parameters: straight, distance, gap, slant, and final waypoint destination. Any of these parameters can be adjusted in the field. Since this equation can use all or some parameters, APOLLO can still make goal selection decisions on limited information.

$$Weight = (d \times P_d) + (a \times P_a) + (\beta \times P_\beta) + (S \times P_S) + (G \times P_G)$$

To select a goal, APOLLO notices the tendency of the path to go in a certain direction, and prefers a path with a similar bearing. Called "slant" (*S*), this is part of the strategy to navigate despite intermittent lines. Another component of the goal selection process, "gap" (*G*), instructs APOLLO to prefer the largest path within selected parameters. Since the maximum and minimum path sizes are known for IGVC, APOLLO will be instructed to prefer paths within these bounds. The other weights in this equation are distance (*d*), angle to waypoint (*a*), and bearing from APOLLO's current direction (β). The goal is then selected by checking each map node with this equation, and marking the lowest value as the goal. The goal is given a weight of zero, the lowest weight on the map. This process is depicted in Figure 6.2. The path selection process consists of three sub-processes: ripple, waterfall, and smoothing.

Ripple assigns increasingly larger weights to map nodes as the distance from the goal increases. A "gradient" is added, which is highest near objects and drops off as distance increases. This modifies the "ripple" values to encourage APOLLO to choose the middle of open areas, reducing risk. Waterfall creates a path for APOLLO by going "downhill." It checks each node from APOLLO to the goal and chooses the lowest number. Because of the weights generated by "ripple," the lower numbers will be closer to the goal. In the case of a tie, a cost equation is used. A special case algorithm has been created for use in the event of flags. Smoothing is needed because the waterfall is restricted to 90 and 45 degree turns only. It uses trigonometry to "cut corners", resulting in shorter path distances.

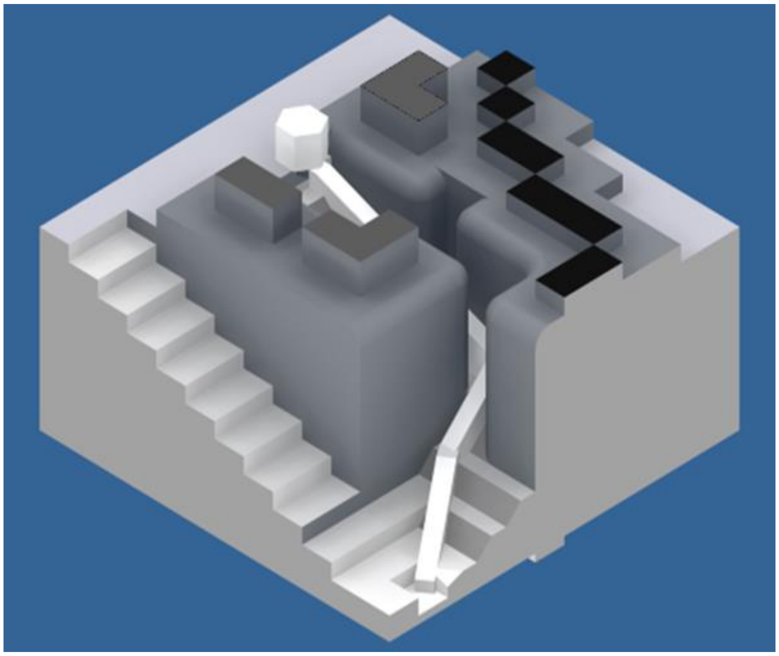

Figure 6.2 APOLLO path planning conceptual Illustration.

After path planning, the speed is determined by the length of the first straight line segment of the chosen path. This allows APOLLO to "open up" in clear areas, and "be careful" in close quarters. Using this path planning process, APOLLO determines both long and short-term goals, allowing it to avoid traps and dead ends.

8. TESTING AND PERFORMANCE

This section will discuss software simulation and predicted performance.

8.1 Simulation

Our custom designed simulation software resides in the same LabVIEW program as the actual navigation software. By simulating APOLLO's logic, we are able to identify problems, examine behaviors, and troubleshoot under any imaginable circumstance. Our simulation is designed to mimic actual APOLLO behavior down to minute detail. All logic in simulation is exactly the same as the logic used in actual field performance. In fact, it is the same software. Through using manufactured sensor data and then feeding this data into the actual APOLLO field program, we are able to determine exactly how APOLLO will make decisions in regards to any obstacle. Furthermore, timers simulating sensor acquisition and additional response time needed due to APOLLO inertial dynamics are part of our program. Also, the simulation can be configured to include any combination of APOLLO's sensors, allowing the team to determine APOLLO's behavior in the event of sensor failure.

8.2 Predicted Performance

APOLLO's base has an absolute maximum speed of nearly 6 miles per hour, so APOLLO is speed-limited in order to meet the IGVC rules. The maximum speed is set to just under 5 miles per hour. With its zero radius turning ability, 6 meter object detection range, and 0.015 second reaction time, APOLLO should be easily able to achieve the 5 mile-per-hour IGVC upper speed limit. The new inclusion of "potholes" in the IGVC course should pose no problems to APOLLO, and can be handled by our vision and path planning. Also, since APOLLO has been specifically designed for exceptional ramp climbing ability, the inclusion of inclines should also pose little threat. It is predicted that APOLLO will perform admirably at IGVC.

9. JAUS

In preparation for the JAUS design challenge, our team has implemented a wireless 802.11 b/g/n Network and the ability to connect over hardwired Ethernet data link as per the IGVC requirements. Port 3794 has been reserved for all JAUS network traffic as well. An interface for waypoint navigation is in development along with an interface that provides remote control status of the system. The local waypoint driver (LWD) and local waypoint list driver (LWLD) interface will provide setup and command capabilities. Velocity and position of the platform will be reported at 10Hz and 1Hz. As per the Remote Control Interoperability Attribute we provide the capability to control a platform via line of sight with remote control commands.

We will have a single navigation and reporting component that accept JAUS commands from the JTC's CVT and COP. In preparation for this, we have simulated JAUS commands from the COP and CVT over a wireless 2.4GHz b/g/n router using our own generated Subsystem ID. JAUS is a platform we consider challenging and are working to improve upon each day. The ability to control our platform remotely, meet the discovery tasks, and report data back about the system's status required a large rewrite of how we handle our system information and allowed us to open up APOLLO to a new and modern form of communication.

10. Failure Points Identification and Resolution

During the design, fabrication and testing we identified the following points of failure, and subsequently included solutions. These problems and solutions are listed below.

a) We discovered that our robot had the tendency to turn around and travel the wrong way on the course.
Solution: We keep a running average of heading. If heading deviates beyond a threshold from the running average, then turn APOLLO and reset the running average to the earlier point.
b) Refusing to move forward because of Glare.
Solution: Software contains anti-glare filters.
c) Getting too close to objects and guide lines on the course.
Solution: Added an optimal amount of "FAT" to the detected objects and lines.
d) Difficulty in differentiating between objects, such as flags from barrels.
Solution: Check for size as well as color of objects.
e) Heat produced by components of APOLLO such as the computer and GPS receiver.
Solution: Installed a cooling unit.

12. COST

APOLLO's total cost to the team was mostly the time devoted to building an optimal intelligent vehicle, however, it did cost the team some monetary expenses. The detailed summary of these costs are in Table 12.1 below.

Item	Cost
Wheel Chair bottom	$1,031
Basler Camera	$1,800
Mareton Compass	$600
Yellow Top Batteries	$240
Laptop	$1,800
Hemisphere GPS	$2,400
Hokuyo LMS	$5,600
Body Fabrication	$280
Other minor Parts	$1,000
Grand Total	$14,751

Table 12.1 Cost Analysis

13. ACKNOWLEDGEMENTS

We would like to thank Two Brothers Collision for providing labor for body fabrication of APOLLO, the WV NASA Grant Consortium for sponsoring our trip to IGVC, the center for Applied Research & Technology for paying for our registration for IGVC 2015, and BSC School of Engineering Technology for supplying parts.