ROBOTICS ASSOCIATION

MOLLEBot

MOdular Lightweight, Load-carrying Equipment Bot

Statement of Effort: I certify that the engineering design of the vehicle described in this report, MOLLEBot, has been significant and equivalent to the effort required in a senior design project. Areas of modification include, but are not limited to, vehicle chassis, sensors and mounting, software design and construction, and electrical implementation.

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5/7/2012

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1. Introduction

MOLLE is an acronym for "MOdular Lightweight Load-bearing Equipment," a named coined by the United States Armed Forces for their backpack systems. As shown in the figure on the title page, MOLLEBot, or MOLLE for short, is a modular, lightweight, back-packable ground robot that has been designed and optimized to best meet the rules and challenges of the 2012 Intelligent Ground Vehicle Competition. While MOLLE is small in stature, she carries a full array of sensors, reliable safety systems, computational equipment and a software system that should make her successful in the dynamic portion of IGVC.

MOLLEBot is a rugged, three wheel, differentially driven robot that was developed specifically for the 2012 Intelligent Ground Vehicle Competition. MOLLE was designed to be inherently small and light, which has multiple advantages in the IGVC. MOLLEbot's small size (just over three feet long and two feet wide) is optimal for passing through narrow openings on the Auto-Nav Course. MOLLEbot's light weight (43 pounds) minimizes the kinetic energy of the vehicle at a given speed. With the recently increased maximum competition speed of 10 mph, minimizing kinetic energy is an important safety consideration. Minimizing vehicle size and mass also results in the efficient use of power and materials. This is an important factor that has a value of 50 points in the IGVC design report scoring criteria. A lighter vehicle is also safer because it uses smaller drive motors and smaller battery packs with less on-board energy storage. It is clear from the IGVC rules that safety is a primary concern of the judges, sponsors and organizers of the competition. Because safety is intrinsically coupled to vehicle mass, developing a capable vehicle of minimum weight should be a fundamental object of the student design teams. In addition to its new mechanical design, MOLLEBot also has a sophisticated software and electrical system vastly different from previous years. New solid-state hardware and a robust and highly cohesive software system will help make MOLLEBot an effective competitor in the 2012 IGVC.

2. Design Process

The team followed a true systems engineering process known as the Spiral Model, **Figure**, for creating and refining MOLLEBot. The spiral model is well suited to the design of complex systems, because it combines advantages of top-down and bottom-up development by prototyping in stages and testing prototyped system as improved designs are developed. By prototyping and testing early, engineers get a firm understanding of what is feasible and desirable. Each design cycle includes developing requirements, system design, implementation and testing. After this the first design cycle is complete, the development cycle starts again in a new iteration by revising the requirements and improving the design. In all subsequent iterations the system is expanded and improved. This process ensures a quality product at the end of the development cycle.

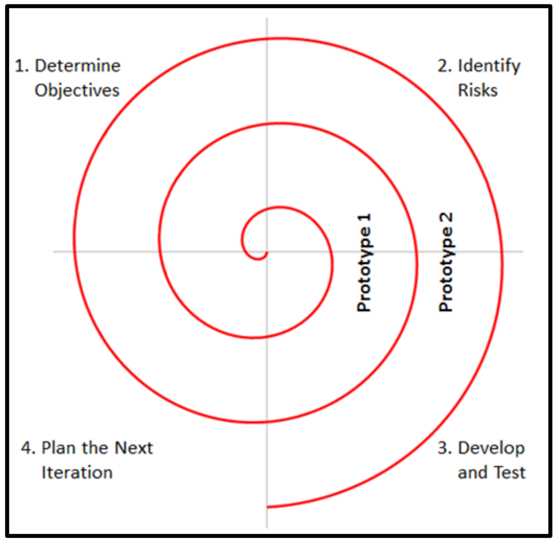

Figure 1: The Spiral Model Design Process

The first iteration of development was based on the wooden vehicle chassis developed for the 2011 IGVC. This prototype allowed the team to brainstorm the redesign of the mechanical system while developing and testing new sensor integration architectures. The control loops layer of software was designed and the interfaces to the sensor layer were defined during this phase. This phase also included integrating the three lower levels of control loops into their respective sensors. Testing in this phase was primarily on the communication interface between sensor and control loop layers.

For the second iteration, requirements were developed that focused on improvements to the phase 1 system. Numerous mechanical improvements, such as the welded aluminum box frame, made the vehicle system safer, more durable and far easier to set up, transport and service. A new printed circuit board was developed for supplying vehicle power, providing remote control operation and for integrating safety systems. Software design focused on refining and tuning the software control loops layer.

In the third design iteration, improvement focused on minor mechanical changes and software. The integration and motion control modules were refined and the full vehicle was field tested.

3. Team Composition

The development of MOLLEBot's system required a multidisciplinary engineering team. The four team members, listed below, put more than 2,000 person-hours into the design, manufacturing, and implementation of MOLLEBot. While the team was made up of a specific group of students that met at weekly, a large group of students, faculty and staff provided ongoing support for the MOLLEBot project. Without them, the creation of MOLLEBot would not have been possible. Student team members are listed in alphabetical order. The contribution column is the primary area of concentration in development. No student's contributions are limited to the single area listed below.

Name	Degree	Class	Contribution
Randy Breingan	Software Engineering	Senior	Software
Christopher Sammet	Mechanical Engineering	Graduate	Electrical
Matthew Standifer	Mechanical Engineering	Sophomore	Electrical
William Meng	Mechanical Engineering	Senior	Mechanical

Figure 2: Team Members and Contributions

4. Innovation

MOLLEBot is innovative in several important respects. Its small size and weight provide obvious advantages, but achieving these characteristics in a durable, reliable, back-packable vehicle required significant innovation. While the team's commitment to innovation should be apparent throughout this report, this section will highlight some of the innovative aspects of the design.

4.1. Innovative Design and Packaging for Reduced Size and Weight

As discussed earlier, minimizing the weight of the vehicle provides for a safer design, and makes efficient use of power and material. Minimizing the size of the vehicle provides distinct advantages in traversing the Auto-Nav Challenge. Given the complex, tortuous maze of obstacles present in recent IGVC competitions, it is not adequate to plan paths by assuming a single point (zero-sized) vehicle translating in a 2-dimensional plane. A compact platform allows for the greatest latitude in planning and executing autonomous maneuvers and in solving the configuration space problem as the robot translates and rotates. Light weight and small size are also important human factors considerations. MOLLEBot was designed to comply with Mil-std-1472F, Table XVII (maximum design weight limits). This standard defines the maximum weight of an object the size of MOLLEBot to be 44 pounds for a female lifting from the floor to a height of three feet.

While the motivation to do so is clear, developing a small, lightweight vehicle brought numerous design challenges. Motor vendors that supply other IGVC teams initially told us our drive motors would be underpowered. Vehicle structural design, material selection, component specifications, and packaging layout became critical design challenges. To meet packaging requirements, the team had to develop a custom integrated circuit board that included power supply and regulation, remote control functions and e-Stop capability. This board will be discussed in greater detail in Section 4 of this report. The team also worked diligently to get a compact Xi3 Modular Computer donated specifically for this competition. The Xi3 is a cube-shaped computer measuring less than 4-inch per side. It is requires less than 20 Watts to operate. Low power consumption helps reduce battery size and cooling requirements.

4.2. Aluminum Box Frame

The previous iteration of MOLLEBot used a wooden monocoque chassis design. While this was relatively easy to fabricate and made an excellent prototype, it was not able to handle cyclic loading. It was difficult to attach the backpack frame to the wooden prototype without compromising other design requirements. The competition version of MOLLEBot uses an aluminum box frame to ensure structural integrity and durability. The current version of the MOLLEBot platform, shown in **Figure 3**: MOLLEBot Fully Assembled**,** has increased the volume of the internal component bay and decreased the overall footprint of the chassis.

4.3. Innovative Stowable Intelligence Gathering System (SIGS)

A complex aspect of designing MOLLEBot was providing mounting structure for the various sensors along with the required emergency stop button and safety light. It is common practice to mount the GPS antenna, camera, compass, and

Figure 3: MOLLEBot Fully Assembled

emergency stop onto a single, tall mast. However, designs with masts are typically large, cumbersome, and awkward to set up. MOLLEBot uses an innovative, low profile sensor integration system called the Stowable Intelligence Gathering System (SIGS). With the SIGS mounting system, the laser range finder and the camera are both mounted on a folding sensor platform near the center of the vehicle. When folded down for backpacking or transport, the platform is flush with the surface of the vehicle. This creates a flat top surface for mounting the backpack and protects the sensors during transport. The backpack frame can also be easily mounted to the chassis. When deployed up for use in collecting sensor data (as shown in the photo of Fig. 3), the Laser Range Finder and the camera are raised to a point where they have a clear view of the course in front of and to the sides of the vehicle.

4.4. Innovative Modular, Highly Cohesive Software

The MOLLEBot software system is simple in its design and elegant in its implementation. The goal of the design was to produce a highly cohesive software system with low coupling. The implementation of asynchronous message passing aided in making this software system simple and robust. Software was broken down into modules such that each sensor, actuator, and control loop had its own executable file. Using asynchronous messages, these software modules broadcast messages to other modules without being directly coupled. Since there are strictly typed message sets for each module, a software module can be easily modified, removed, or completely replaced without any changes in the other modules.

5. Electrical System Design

MOLLEBot uses a SICK LMS 151 scanning laser range finder, a NovAtel GPS system, a PNI TCM2 compass, and a GoPro HD Hero camera for perception. A comprehensive list of components is provided in section 7.1, Component Costs. Since many of the other vehicles at competition use similar sensor packages, this report will focus more on the integration of the sensors and the design of the supporting electrical system.

The electrical system is one of the more complex subsystem, and it generally has a high number of potential failure points. For this reason, the team spent substantial time working to design and document the electrical system of MOLLEBot before implementing it in hardware. Every detail of the electrical system cooresponds to a design requirement.

5.1. Custom Power Distribution and Control Circuit

This year, the MOLLEBot team designed and manufactured a custom power distribution and control circuit board. Shown in **Figure 4**: MOLLEBot's Custom Power and Control the custom pc board provides all the necessary operating voltages for ech of MOLLEBot's componenets. Each voltage that is required by MOLLEBot's components, 12V, 5V, and 3.3V, are provided by this circuit and each has an extra socket to allow for new componenets to be integrated in the future.

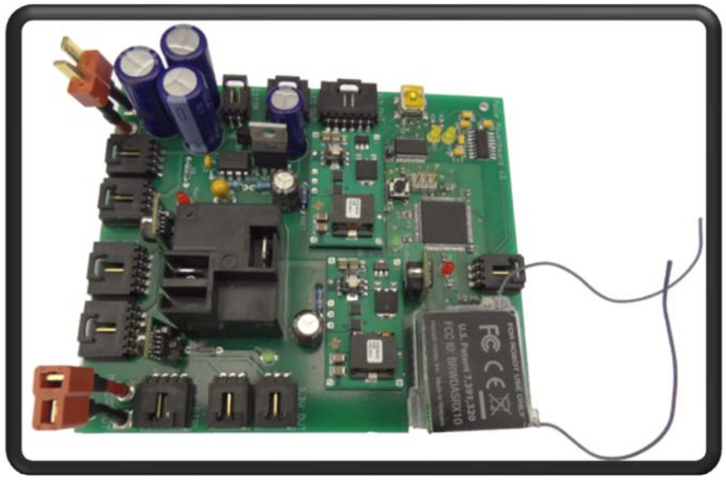

Figure 4: MOLLEBot's Custom Power and Control Board

The board also provides remote control function from an R/C transmitter and both wired and wireless e-Stop capability. This all-in-one board is critical to the compact packaging layout in MOLLEBot.

5.2. Improvement of Motor Interface

Previous iterations of MOLLEBot used an analog voltage line to command the Quicksilver A23H-5 motors. This worked well except when the motors were turned on before the R/C controller was turned on. In this case, the analog input of zero volts would command the motors to full reverse. Now, for safety and interoperability with other software packages being developed at Embry-Riddle, the remote control solution and the command interface from the computer have been integrated into one microcontroller on MOLLEBot's custom power and control board. This board communicates with the motor controllers through an RS-232 serial line. An electrical system layout is provided in **Figure 5**.

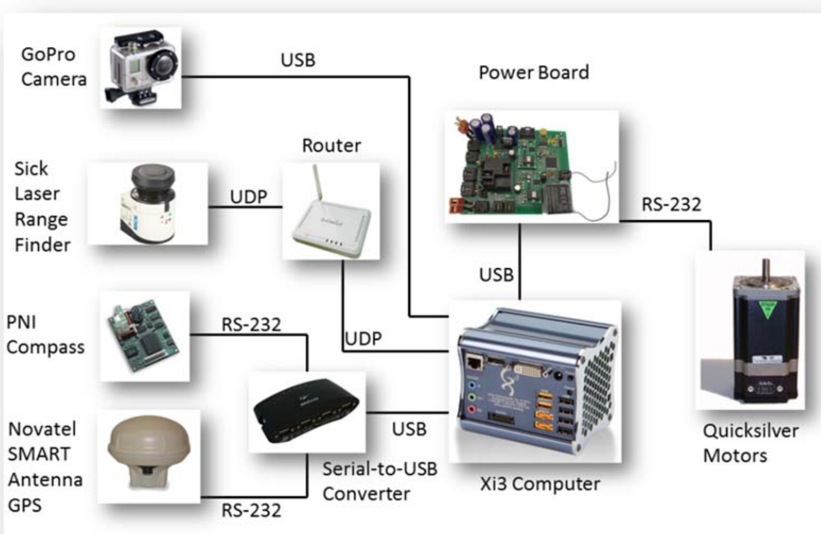

Figure 5: Electrical System Flow Chart

5.3. Battery Safety

During the design phase of the project, the team considered several battery chemistries for use on MOLLEBot. Lithium Polymer (LiPo) batteries have the highest energy density, which is important for a lightweight vehicle. However, LiPo's can be potentially dangerous if they are not not handled properly or if the vehicle is damaged in a collision. For this reason, the team selected A123 Nano phosphate Lithium Ion battery cells due to their safety and similar energy density to LiPo's. Thanks to a donation from DeWalt, the team was able to construct custom battery packs, show in **Figure 6**: Custom A123 Battery Packs, from A123 cells to get the 24V operation voltage required by the power system. Note also that the battery packs are wrapped in high-visibility orange packaging material to make them visible for service or in the event of an emergency. This bright orange battery packaging is required in other AUVSI competitions and is becoming standard practice on many electric vehicles.

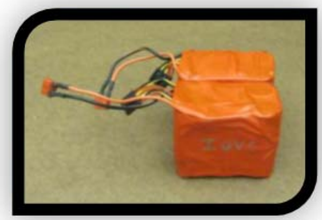

Figure 6: Custom A123 Battery Packs

6. Software Design and Systems Integration

MOLLEBot had a group of Software Engineering students dedicated to designing the software system from the ground up. By writing a formal software requirements specification and ending with a full implementation of the design, the software team followed the full life cycle of the software.

Many of The Robotics Association's industry partners develop software in C++ under a Linux based operating system (OS). Use of C++ and Linux is the prevalent solution in the autonomous systems industry. Given this preference, the team decided to undertake the MOLLEBot software development using the same development environment. MOLLEBot's onboard computer uses the Ubuntu OS and the g++ compiler to operate efficiently and effectively. MOLLEBot also utilizes the Robot Operating System (ROS), a meta-operating system that provides functionality common to robotic applications and OpenCV, the open source computer vision library.

6.1. Software Architecture

MOLLEBot was designed to have a modular software system that is easily modified. As such, the software could be expanded and enhanced without requiring a significant overhaul of the software. The software was broken down into independent modules that could be written and operated completely independently of each other. The initial design of modules is shown in **Figure 7**.

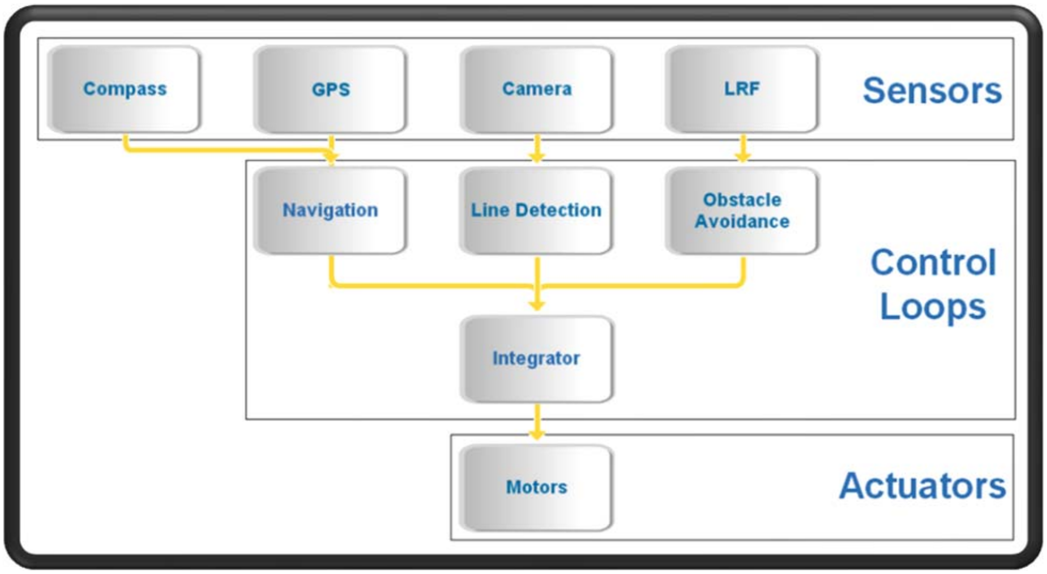

Figure 7: Software Modules

Each sensor has a software executable that will run independently of all other software in the system. When new data is received by the module, it will broadcast, in a strictly typed message, what was received over a private communication channel to a control loop module that will then process the data. This makes it easy to modify or replace the communication to sensors because it does not affect any of the other software. A control loop module is an event-based system. Upon receipt of a message, the module will execute once, updating necessary information and broadcasting it, and then sleep until another message is ready. When a message is received, the software will calculate a vector to its desired direction. This vector is then passed to the integrator, which is also event based, like a control loop, but instead of calculating a vector it will calculate motor speeds and broadcast the commands accordingly.

6.2. Mapping Technique

Various types of mapping algorithms, including occupancy grids and simultaneous localization and mapping (SLAM) algorithms, have been developed for autonomous vehicle student projects at Embry-Riddle. The MOLLEBot team decided to focus on robust local mapping algorithms, MOLLEBot builds a localized map that contains course and obstacle information based on data acquired over the last few seconds. This local map is updated so that obstacles that disappear from the field of view are assumed to move backwards over time, having less of an effect on the integrator algorithm as it moves backwards, but still contributing so that the rear of the vehicle does not hit the obstacle. The path of the vehicle around an obstacle resumes its initial path and therefore looks like the diagram in **Figure 8**.

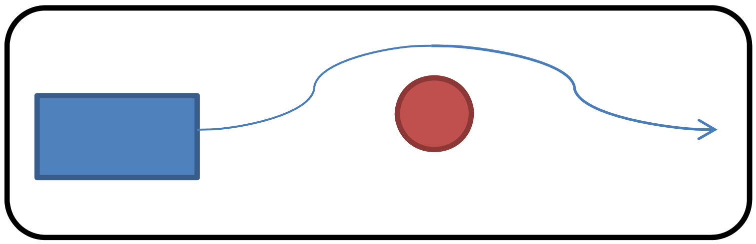

Figure 8: Vehicle Path around Obstacle

6.3. Lane Following

In the Line Detection module, MOLLEBot uses the simple brightest pixel algorithm, shown in **Figure 9**, for detecting lines and identifies a single point on the line using ground plane interpolation of the pixel coordinate.

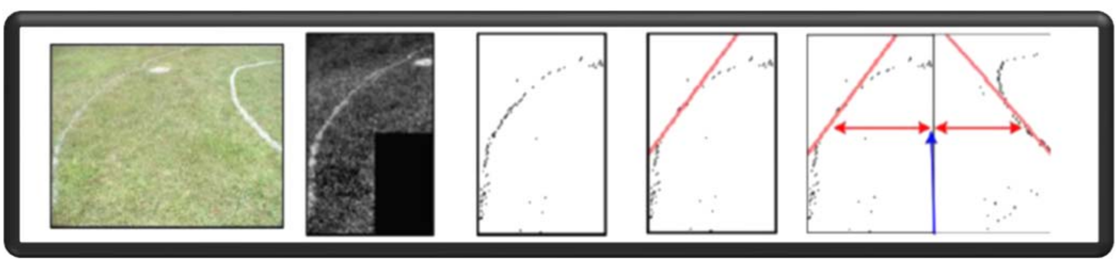

Figure 9: Line Detection

Once the lines are detected, a single point on each line is selected at a specified distance from the vehicle. These two points then become virtual obstacles in the software. The Line Detection module broadcasts a vector that points directly between the two points identified. An example of the point identification is shown in **Figure 10**.

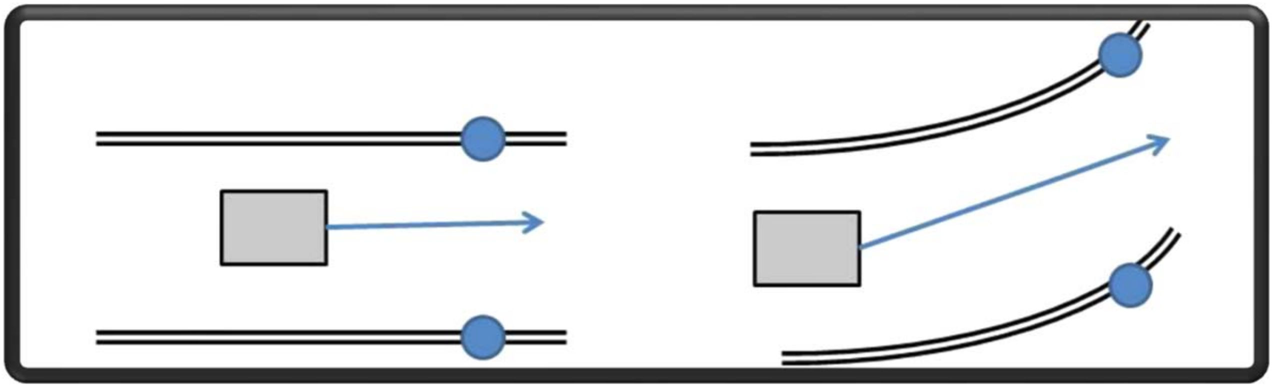

Figure 10: Vector Generation from Line Detection

6.4. Obstacle Detection

The Obstacle Avoidance module takes data in from a scanning laser range finder as an array of vectors. MOLLEBot selects a subset of these vectors that are closest to the vehicle, the most hazardous to the vehicles current location and calculates the shortest path away from these obstacles.

6.5. Waypoint Navigation

The Navigation module keeps track of the waypoints that the vehicle is required to navigate through. This module identifies its position and heading relative to true north from data that it receives from the GPS and compass broadcasts. Using this information and the recorded information about the waypoint path, MOLLEBot calculates the distance and angle to the waypoint. The module then broadcasts this information for receipt by the Integrator.

6.6. Data Integrator

Once any of the control modules have completed their tasks and sent their data over the broadcast channel, the Integrator module will read the data and update the motor values accordingly. To do this, the Integrator module is broken down into sections that are cascading in sequence.

If the Line Detection module completes an execution of its control loop and broadcasts a new vector before the Obstacle Detection or Navigation modules finish, then the Integrator will only execute the Line Integration function, making the assumption that the vector produced by transition 2 is still valid from the previous iteration of the Integrator, as seen in **Figure 11**.

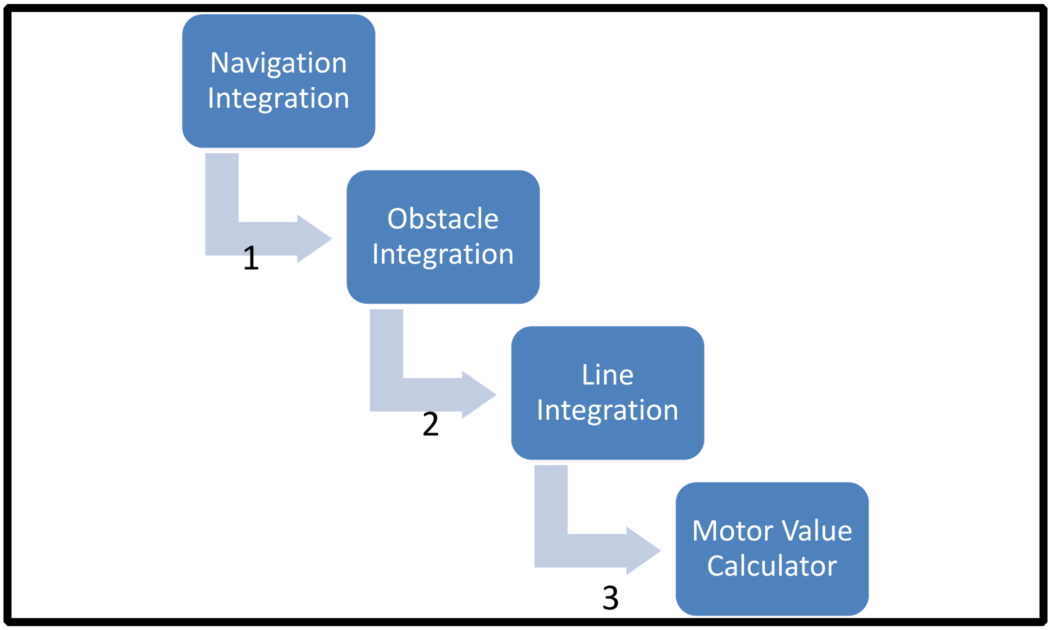

Figure 11: Waterfall Sequence

7. System Design and Integration

The challenge posed by the Intelligent Ground Vehicle Competition is one that cannot be tackled solely with Mechanical Engineering, Software Engineering, or Electrical Engineering practices. The problem is fundamentally one of Systems Engineering. No modern robotic vehicle can be successful without a structured systems integration plan. Each team member needs to be cognizant of how their decisions will impact the design and engineering approach of other team members.

7.1. Component Costs

Due to the sponsors of our organization, MOLLEBot was able to be constructed at minimal cost to the team. **Figure 12** shows a list of components that were used in MOLLEBot, with the cost to the team and estimated market value.

Component	Cost to Team	Market Value
A123 Battery Packs (4 Cell)	Donated by DeWalt	$108.00
Aluminum Frame	$500.00	$500.00
Caster Wheel	$15.00	$15.00
Keyspan Serial to USB	$114.00	$114.00
Xi3 Modular Computer	Donated by Xi3	$800.00
NovAtel GPS	$5,000.00	$5,000.00
Quicksilver Motors	$1,550.00	$2,200.00
SICK LMS151	Donated by Geared to Learn	$7,632.90
Skyway Wheels	$60.00	$120.00
PNI TCM2 Digital Compass	Donated by PNI Corp	$700.00
GoPro Camera and adapter	$180.00	$180.00
Custom Power Circuit	$100.00	$100.00
Wires and Misc.	$200.00	$200.00
TOTAL	$7719.00	$17,669.90

Figure 12: Component Costs

8. Safety, Reliability and Durability

Safety is a primary concern at all times while working on MOLLEBot, or any robotic project. Laboratory rules were strictly enforced for any student participating on the MOLLEBot team. In order to join the team each member must watch a safety training video that explains how to safely operate equipment in the lab, how to handle an emergency, and general safety rules. Safety goggles were worn throughout the build process, except during software construction.

8.1. Emergency Stop Functionality

The hard-wired electronic emergency stop button is located on the back mast at the rear of the vehicle. This button disengages a relay, cutting power to the motors and rapidly stopping the vehicle. The remote control receiver and processor provide a wireless estop that can be engaged at any time.

8.2. Remote Controller

The remote control system used in MOLLEBot ensures that the controller must be on and in range for operation of the vehicle to continue. If the signal from the controller is disrupted the system goes to a state where motors are continually commanded to zero movement. This will prevent the vehicle from rolling if on a slope, as well as, prevent the computer from commanding new motor values. The wireless receiver will operate up to .25 miles away. Should the vehicle lose the wireless connection with the controller, it will immediately go into emergency stop mode.

8.3. Reliability

MOLLEBot uses many commercial, off-the-shelf components. In keeping with the systems engineering approach taken in the design of MOLLEBot, these components fit well into the design and provide a high level of reliability. Each item was carefully integrated with voltage regulators, power switches, and mounting hardware. With different voltage levels inside MOLLEBot, the electrical system was implemented such that no device could be plugged into the wrong voltage source. Each different voltage level has a different connector that will not interface with the others. This ensures that anyone can set MOLLEBot up and it will run the same way that it has every time in the past.

9. Predicted Performance

MOLLEBot uses two QuickSilver QCI-A23 H-5 motors with integral 15:1 planetary gear head reducers. The motors run at 36V and produce 190oz-in of torque at 5mph while drawing only about 4 amps. Each drive wheel weighs 5.65 lbs including the motors, gear heads, hubs and mounting clamps. The motors run at a maximum speed of 4000 rpm. With 12.5 in diameter tuff wheels, this results in a maximum vehicle velocity of 9.91 mph. This maximum speed can be limited through firmware settings in the motor controllers.

At peak torque, each motor is capable of generating 28.5 pounds of tractive force against the ground. With both wheels driving, the vehicle therefore has sufficient torque to lift its own weight and drive vertically up a wall (assuming driving frictional could be maintained) at speeds just above stall. With 120 oz-in of torque available at 1000 rpm, the motors can easily drive up the ramp at 2.5 mph with ample torque to spare.

Battery life is also enhanced by MOLLE's lightweight design. The largest power consuming components are the drive motors (108 Watts maximum power draw per motor) and the Xi3 computer (20 Watts maximum power draw). All other components draw about 70 watts combined, so the total theoretical maximum power draw of the vehicle under full load is about 300 Watts. The 16 cell battery pack on MOLLE has 116 Watt-hours of energy, so under full load the batteries should be expected to last about 23 minutes. In typical field operation, the vehicle is running at an average of 55 Watts (based on measurements taken with an inline power meter), which should give about two hours of run time. In all of our testing, the batteries have run for well over an hour.

10. Conclusion

MOLLEBot is a fully autonomous robotic vehicle, designed, manufactured and tested by engineering students at Embry-Riddle. The team developing MOLLEBot gave special attention to current IGVC rules, which require the system to intelligently switch between autonomous roadway following mode and GPS waypoint tracking. The team also considered customer requirements such as efficient use of power and materials; attention to safety, reliability, and durability; the desire for innovation. Designed through a spiral systems engineering process, MOLLEBot is a simple, robust, and elegant solution to the problem posed by the 2012 IGVC. By following a methodical engineering design process, by using the latest software tools, and through rigorous testing, the team was able to create a vehicle that should compete favorably in the 2012 Intelligent Ground Vehicle Competition.