EMBRY-RIDDLE
Aeronautical University
ROBOTICS ASSOCIATION

MOLLEBot III

Mobile Lightweight Load-carrying Equipment Robot

Statement of Effort: I certify that the engineering design of the vehicle described in this report, MOLLEBot III, 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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1. Introduction

This report describes the design, development and systems integration of an innovative third-generation autonomous vehicle named MOLLE III (Mobile Lightweight Load carrying Equipment Robot). The new generation of MOLLE retains the most desirable features of the earlier iterations including portability, ruggedness, and remarkable agility in operation. In addition, MOLLE III has been redesigned mechanically to provide additional interior space for mounting hardware, better payload-carrying capability, significantly improved ground clearance, a more comfortable and direct user interface, better sensor mounting locations and a viscoelastic leaf-spring suspension to help isolate sensitive equipment. Performance on the AutoNav courses should be greatly improved by a new software system developed using the LabVIEW programming environment. The design focus for both hardware and software was to produce an autonomous vehicle system that was elegant in its simplicity and competitive in operation.

2. Design Process

The team followed a systems engineering process known as the Spiral Model for creation and refinement of MOLLE III. A graphic of this process is shown in Figure 1. The spiral model is well suited to the design of complex systems due to the combined advantages of top-down and bottom-up development by prototyping in stages and testing prototyped systems as designs are developed. By prototyping and testing early, engineers get a firm understanding of what is feasible and desirable. Each design cycle includes development of requirements, system design, implementation and testing phases. Once the first design cycle is complete and 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 helps ensure a quality product at the end of the development cycle.

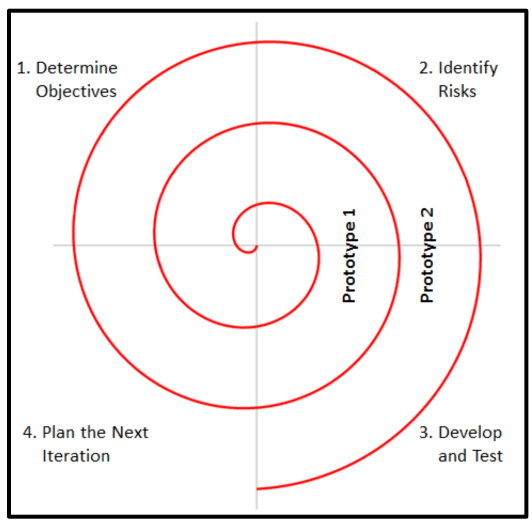

Figure 1: The Spiral Model

This year, the first iteration of development began with the aluminum vehicle chassis developed for MOLLE II in the 2012 IGVC. This prototype allowed the team to envision the redesign of the mechanical system while developing and testing new software and sensor integration architectures. The control loops layer of software was designed and the interfaces to the sensor layer were refined during this iteration.

During the second iteration, requirements were developed that focused on improvements to the system. Numerous innovations followed: a new chassis, a simple viscoelastic suspension, and direction-indicating LED lighting. These innovations make the vehicle system safer and more durable, as well as easier to construct, set up, transport, operate, and service. Even more refinements and augmentations followed such as small changes to the printed circuit board that supplies vehicle power, remote control operation, and integrates the safety systems. Software design focused on developing and fine tuning the new LabVIEW-based software navigation module. For the last design iteration improvement was focused on minor mechanical changes and software refinements.

3. Team Composition

The development of MOLLE III's system required a multidisciplinary engineering team. The team put more than 2500 man-hours into the design, manufacturing, and implementation of MOLLEBot. While the team was made up of a specific group of students that met weekly, a large group of students, faculty, and staff provided ongoing support for the MOLLEBot project. Student team members are listed in alphabetical order in Table 1.

Table 1: Team Members and Contributions

Name	Degree	Contribution
Charles Breingan	Mechanical Engineering	Software
Gene Gamble	Software Engineering	Software
Christopher Sammet	Mechanical Engineering	Mechanical/Electrical
Elizabeth Worsham	Mechanical Engineering	Electrical
Tim Zuercher	Mechanical Engineering	Mechanical/Electrical

4. Innovations

Teams competing in the IGVC have a long running trend of designing large, complex vehicles. The MOLLE III platform offers a compact, tightly integrated design (shown in Figure 2). This section of the report will highlight a few of the unique innovative aspects of the design.

4.1. Small, Lightweight, and Easily Manufactured

Size does not equate to performance and after years of observing massive cumbersome robots in competition, the team determined that the optimal solution was to aim for a more compact and light weight vehicle. Minimizing the weight of the vehicle provides for a safer design, and makes efficient use of power and material. This provides distinct advantages in traversing the Auto-Nav Challenges. 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.

Figure 2: MOLLEBot 2013

While the benefits of a small lightweight vehicle are clear, developing a compact vehicle brought numerous design challenges: vehicle structural design, material selection, component specifications, and packaging layout. In order to meet packaging requirements, the team had to develop a custom integrated circuit board that included power supply regulation, remote control functions and e-Stop capability. The MOLLE III frame is constructed out of readily available wood. Because of this, MOLLE III can be built from the ground up in an afternoon. MOLLE III's construction also allows for quick in the field modifications and repairs. These repairs and modifications can be made and reversed on the fly, allowing for quick turnaround prototyping and testing of new features.

4.2. Direction Indication Lighting

One of the biggest problems faced by teams designing a robot for the IGVC is safety. Robots competing in the IGVC are generally large and heavy and can be quite dangerous. When an autonomous robot is active it is difficult for those observing it to predict which way the vehicle plans on moving. MOLLE III addresses the size problem by fitting the minimum dimensions and being lightweight. In order to eliminate the uncertainty of direction problem the team has placed direction indicating LED lighting on the vehicle. This lighting turns on in the direction the vehicle plans on moving allowing bystanders to better predict the vehicles movement.

4.3. Monocoque Frame

The first iteration of MOLLE used a frame and box design. The frame structure of the vehicle took up a large amount of space, and the electronics compartment was formed by externally attached, non-structural paneling that provided poor mounting points for components. In the current iterations the team adopted a monocoque construction design. The structure of the vehicle is now doubles as the electronics enclosure. This more than doubled the internal capacity for electronics and other components, provides more flexible mounting locations, and is also lighter than other frames.

4.4. Modular, Highly Cohesive Software

The MOLLE III 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 incredibly robust. Software was broken down into modules such that each sensor, actuator, and control loop has its own LabVIEW VI. 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

4.5. Novel Viscoelastic HDPE Cantilever Arm Passive Suspension

Recent changes in the rules for IGVC allow and encourage higher vehicle speeds. At the maximum allowable speed of 10mph, overall vehicle dynamics become important. To help attenuate the vibration and shock loads through the drive wheels (which carry that majority of the vehicle weight), a simple cantilever-beam suspension was implemented. The drive motors are mounted to a high-density polyethylene (HDPE) beam. The transverse beam is fixed to the chassis in the center, and the gear, motors, and wheels are mounted to the outboard ends of the beam. According to Eke, et. al. [2012], among all the polymers, HDPE exhibits the best combination of a high loss factor (the ability to absorb energy), relatively low density and high Young's modulus (stiffness). This simple suspension provides additional isolation and protection for the sensors and electronics.

5. Electrical System Design

MOLLE III uses a SICK LMS 151 scanning laser range finder, a NovAtel GPS system, a Sparton GDEC6 compass, and a GoPro HD Hero 2 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 section will focus more on the integration of the sensors and the design of the supporting electrical system.

5.1. Custom Power Distribution and Control Circuit

The electrical system is one of the more complex subsystems in a robot, 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 MOLLE III before implementing it in hardware. Every aspect of the electrical system corresponds to a design requirement. The MOLLE III team designed and manufactured a custom power distribution and control

Figure 3: MOLLEBot's Custom Power and Control Board

circuit board. Shown in Figure 3, the custom printed circuit board provides all necessary operating voltages for each of MOLLE III's components. In addition, each voltage has an extra socket to allow for new componenets to be integrated in the future. 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 MOLLE III.

5.2. Improvement of Motor Interface

Previous iterations of MOLLE III have used an analog voltage line to command the Quicksilver A23H-5 motors. This design worked well except in the case where 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. To solve this, and 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 MOLLE III'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 4.

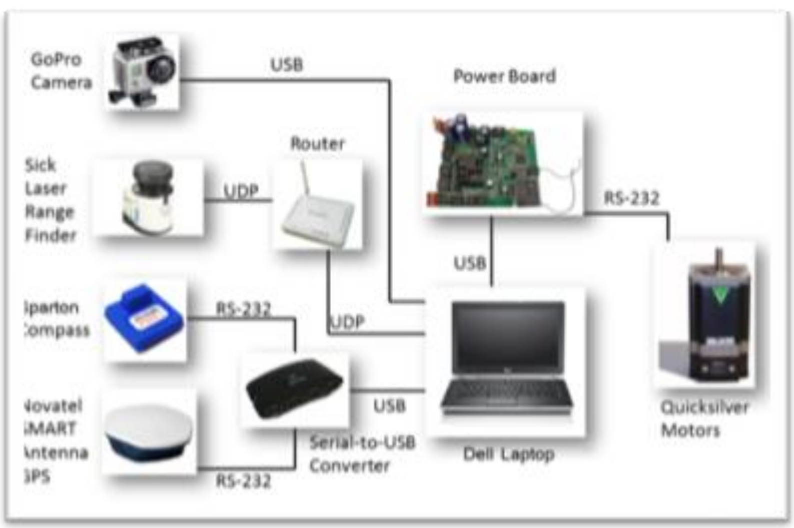

Figure 4: Electrical System Flow Chart

6. Software Design and Systems Integration

LabVIEW was chosen as the development environment for MOLLE III for its ease of use, rapid iterative development capabilities, multidisciplinary applications, and available toolkits. LabVIEW provides a large number of prebuilt module blocks which can be used such as vision processing, protocol communication, and a full robotics toolkit which provides functionality common to robotic applications. In order to simplify the execution of the software and reduce the need for external monitoring devices, MOLLE III makes use of an onboard Dell laptop running Microsoft Windows 7 with a four core Intel i5 processor running at 2.5GHz with 4GB of RAM.

6.1. Software Architecture

MOLLE III was designed to have a modular software system that is easily modified. As such, the software can be expanded and enhanced without requiring significant overhaul. The software was broken down into independent modules that can be written and operated completely independently of each other. Module data flow is shown in Figure 5.

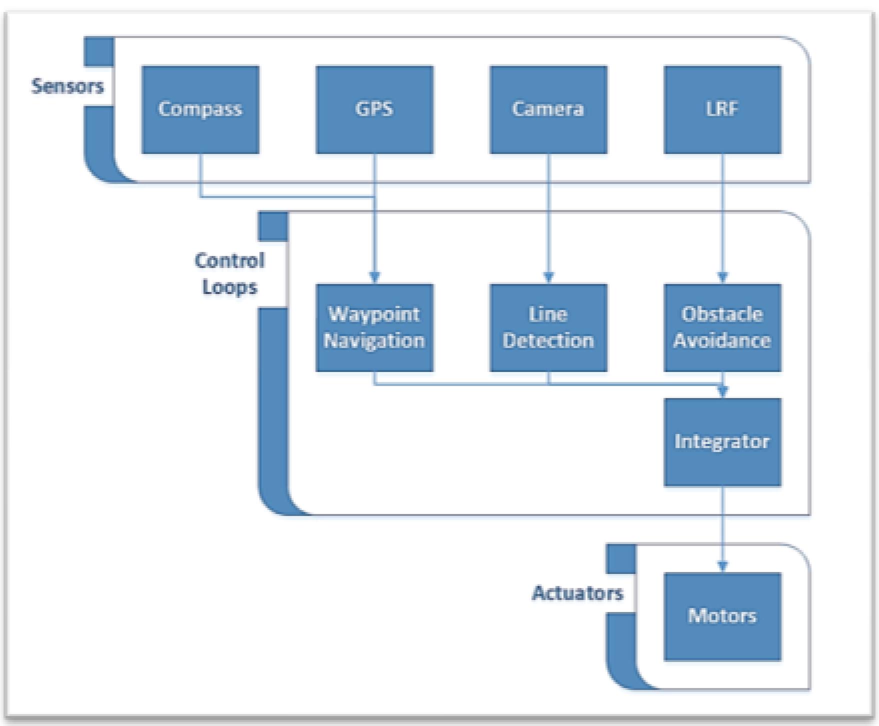

Figure 5: Software Modules

Each sensor has a LabVIEW VI 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, the data to a message queue that the control loop module will read and use to 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. Each control loop module operates as 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 by a control loop module, the software will calculate a vector pointing to its desired direction of travel and virtual obstacles to be added to a localized occupancy grid for the path planning algorithm. The vector is then passed to the integrator, which is also event based, like a control loop, but instead of calculating a travel 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. MOLLE III builds a localized occupancy grid that contains course and obstacle information based on data acquired over the previous 30 feet the vehicle moved. The map holds the local position of the vehicle, obstacles, lane locations, and a goal waypoint position. The goal waypoint is either the next given course waypoint or a virtual waypoint which is placed 20ft in front of MOLLE III on the local map. 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, 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 6 .

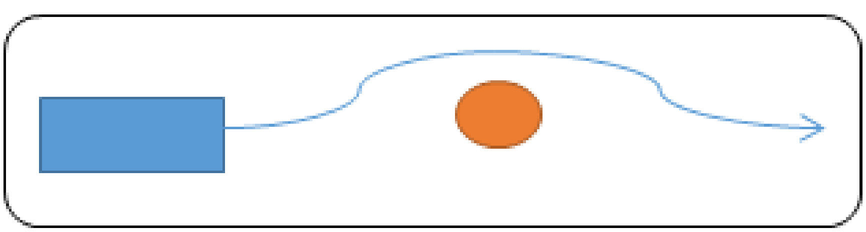

Figure 6: Vehicle Path around Obstacle

6.3. Lane Following

In the Line Detection module, MOLLE III uses a simple brightest pixel algorithm, shown in Figure 7, for detecting lines and identifies a single point on the lines on either side of the vehicle using ground plane interpolation of the pixel coordinates. The points on the lines are calculated by using a Hough transform, as such both solid and dashed lines are detected.

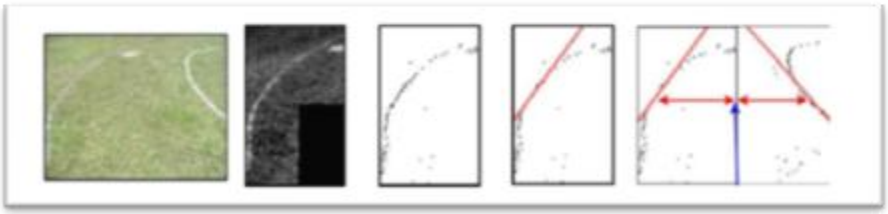

Figure 7: Line Detection

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 software. The Line Detection module broadcasts the local position of the two points identified along with a vector that points directly between the two points to the Data Integrator. An example of the point identification is shown in Figure 8.

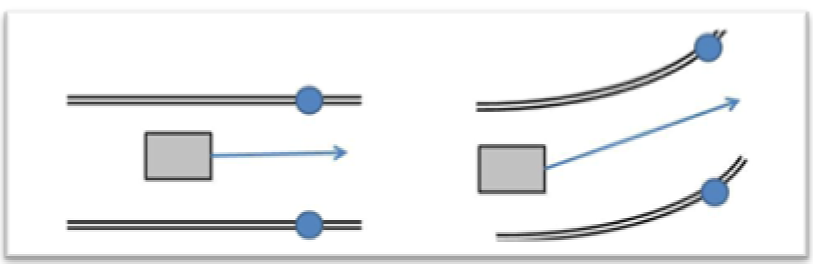

Figure 8: Vector Generation from Line Detection

6.4. Obstacle Detection

The Obstacle Avoidance module takes data in from a scanning laser rangefinder as an array of vectors representing objects surrounding the vehicle in a 270 degree field of view. MOLLE III filters a subset of these vectors to identify potential obstacles within a 15ft range of the vehicle. A vector leading away from the closer objects in a direction relative to the current direction of the vehicle is then calculated. The coordinates of the obstacles along with a vector pointing to the shortest path away from the most hazardous obstacles are then broadcast to the Data Integrator.

6.5. Waypoint Navigation

The Navigation module keeps track of the waypoints that the vehicle is required to navigate through and of the virtual waypoint from the mapping module. This module identifies its position and heading relative to true north from data that it receives from the GPS and compass broadcasts. The Navigation Module also determines when the virtual waypoint or the given course waypoint is set as the goal waypoint. Using this information and the recorded information about the waypoint path, MOLLE III 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 obstacle detection and navigation are still valid from the previous iteration of the Data Integrator, as seen in Figure 9.

Figure 9: Waterfall Sequence

The path calculator then uses the localized occupancy grid to calculate a potential path to the current goal waypoint using the D* search algorithm. The D* search algorithm will allow the vehicle to navigate through complex navigation portions such as switchbacks. A vector pointing to the next fragment of the path is then calculated from the D* result to provide the motor drive vector. The motor drive vector is then amended with the control loop vectors to avoid hazards which may be missed or ignored by the D* algorithm such as the edges of obstacles.

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. Using the Spiral Model the team constantly prototypes, integrates, and tests vehicle components to find the best configuration for MOLLE III.

7.1. Component Costs

Due to sponsorships, MOLLE III was able to be constructed at minimal cost to the team. Table 2 shows a list of components that were used in MOLLE III, with the cost to the team and estimated market value.

Table 2: Component Costs

Component	Cost to Team	Market Value
Lipo Battery Packs (6 Cell)	$60.00	$60.00
Wooden Frame	$80.00	$80.00
Caster Wheel	$15.00	$15.00
Keyspan Serial to USB	$115.00	$114.00
Dell Laptop Computer	$0.00	$1000.00
NovAtel GPS	$4,500.00	$5,000.00
Quicksilver Motors	$1,550.00	$2,200.00
SICK LMS151	Donated by Geared to Learn	$7,633.00
Skyway Wheels	$60.00	$120.00
Sparton GDEC6 Digital Compass	Donated by Sparton Corp	$1350.00
GoPro Camera and adapter	$180.00	$180.00
Custom Power Circuit	$140.00	$100.00
Wires and Misc.	$200.00	$200.00
TOTAL	$6900.00	$18053.00

7.2. Safety and Durability

Safety is a primary concern of any robot. To improve the safety of MOLLE III the team built a smaller vehicle, installed direction indication LED's, and implemented multiple E-Stop systems. MOLLE III has had its durability increased through the new chassis design and the implementation of a passive suspension system.

7.3. 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.

7.4. Remote Controller

The remote control system used in MOLLE III 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 and prevent the computer from commanding new motor values. The wireless receiver will operate up to 0.25 miles away. Should the vehicle lose the wireless connection with the controller, it will immediately go into safe mode.

7.5. Reliability

MOLLE III uses many commercial, off-the-shelf components. In keeping with the systems engineering approach taken in the design of MOLLE III, 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 MOLLE III, 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.

8. Predicted Performance

MOLLE III uses two QuickSilver QCI-A23 H-5 motors with integral 15:1 planetary gear head reducers. The motors run at 24V 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 2700 rpm. With 12.5 in diameter tuff wheels, this results in a vehicle velocity of 6.7 mph. If the motors are driven with 36V, the vehicles maximum velocity is 9.9 mph.

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 friction could be maintained) at speeds just above stall. With 120 oz-in of torque available at 1000 rpm, the motors can drive up the ramp at 2.5 mph.

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). All other components draw about 70 watts combined, making the total theoretical maximum power draw of the vehicle under full load about 300 Watts. The 6 cell lithium polymer battery 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.

The independent module software design for MOLLE III allows for the detection of obstacles up to 15ft away in the localized occupancy grid. This allows approximately 11 seconds for the vehicle to avoid an obstacle at the minimum 1 mph speed and 2.5 seconds at 6.7 mph. The software system is capable of reacting to new obstacles and lines in a maximum of 150ms. Complex obstacles will be handled by the D* path planning algorithm. Finally, with the use of the Novatel GPS, waypoints can be navigated to within 1.5ft.

9. Conclusion

MOLLE III is a fully autonomous robotic vehicle, designed, manufactured and tested by engineering students at Embry-Riddle. The team developing MOLLE III 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; and the desire for innovation. Designed through a spiral systems engineering process, MOLLE III is a simple, robust, and elegant solution to the problem posed by the 2013 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 Intelligent Ground Vehicle Competition.

10. Reference

[1] Ege, K., Boncompagne, T., Laulagnet, B., & Guyader, J. L. (2012). Experimental estimations of viscoelastic properties of multilayer damped plates in broad-band frequency range. arXiv preprint arXiv:1210.3333.