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Leveraging the Agile Process and Technical Advancements for the Intelligent Ground Vehicle Competition

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Abstract: The Intelligent Ground Vehicle Competition (IGVC) is an annual robotics competition sponsored by the United States (US) Combat Capabilities Development Command – Ground Vehicle Systems Center (GVSC). Teams from universities design robot prototypes to autonomously navigate an obstacle course. Team success is judged by the robot's successful navigation of the course and total time to traverse the course. A sprint-based agile design approach and integration of cutting-edge technology were integral to the USMA team's ability to design and develop an autonomous ground vehicle. The USMA designed robot, named Intelligent Vehicle of Autonomous Navigation (IVAN), utilizes state-of-the-art sensors and computing hardware to achieve autonomous navigation. Sensor outputs from a camera and laser rangefinder are integrated and processed by a neural network for determining the best navigational path. IVAN is a powerful, reproducible, and applicable solution to GVSC's problem of creating the next generation of autonomous robots capable of self-navigation in challenging environments.

Keywords: Autonomous Robotics, Neural Network, Obstacle Avoidance, Agile Development

1. Introduction

1.1 Overview of the Intelligent Ground Vehicle Competition

The Intelligent Ground Vehicle Competition (IGVC) is an annual challenge in which undergraduate teams design and race autonomous robots across an obstacle course. The United States Military Academy's IGVC team developed a robot that utilizes the latest technologies in sensory and computing hardware. The team leveraged middleware known as Robot Operating System (ROS) to modularize the system design into algorithmic nodes and interconnect them using ROS's message passing framework. Robot Operating System (ROS) is an open source framework which is recognized for its flexible modular structure that speeds up the development process. ROS was created by Scott Hassan and his research lab, Willow Garage, with the goal of expediting the process of building robots (Wyrobek, 2017). By sharing a common software framework, the community of ROS users can easily share code in the form of packages or modules. These modules range from common hardware drivers to complex path planning algorithms. The ability to download these modular algorithms and repurpose them in a custom robot design greatly reduces the time required to build robots (Quigley, Gerkey, and Smart, 2015). The constraints for the design of the team's robot, Intelligent Vehicle of Autonomous Navigation (IVAN), for the IGVC are outlined in the competition performance guidelines and the additional team-identified constraints below.

1.1.1 2019 IGVC Guidelines

All robots entered in the IGVC competition must be built to meet known design specifications and be capable of achieving performance requirements. The 2019 IGVC course is a 600-foot long course on a grass field (IGVC, 2018). Boundaries are designated by continuous or dashed white lines approximately three inches wide, painted on the grass. Autonomous vehicles must traverse the course and remain within the boundaries. The alternating dashed lines are 15-20 feet long, with 10-15 feet separation. A minimum speed of one mph is required while the robot remains on the course. If a vehicle does not average one mph for the first 44 feet from the starting line of the course, the vehicle's run will be terminated. The course contains both natural or artificial inclines with gradients no greater than 15%. Naturally occurring obstacles as well as man-made obstacles such as various colored construction barrels/drums, light posts, and street signs can be found on the course. Robots must avoid touching these obstacles; otherwise, the trial is terminated. Vehicles must complete the course within six minutes (IGVC, 2018). These guidelines act as performance requirements against which the team's design is measured.

1.1.2 IGVC Constraints

Competing robots must meet specific design constraints. A robot must be over three and less than seven feet in length. It must have a width between two and four feet. The maximum height is six feet tall excluding any emergency-stop antennas. Each robot must have a mechanical and wireless emergency stop button. The mechanical button must be located between two and four feet in height. The wireless emergency stop must work up to a minimum of 100 feet within the robot. IVAN must have a safety light that will signify its driving mode (autonomous or manual). The robot cannot exceed a speed of five miles per hour but adhere to a minimum speed requirement of one mile per hour. Within the six-minute time limit, the robot must demonstrate that it can detect and follow the white painted lanes, avoid obstacles, and find a path to a single two-meter wide navigation waypoint (IGVC, 2018).

1.2 Overview of the Agile Methodology

The USMA team used the agile method as the project management methodology for the development of IVAN. The agile method of project management allowed the team to divide our tasks into subtasks, assign roles to each group member, and stay organized to ensure progress was made (Ghahri, 2018). Within the agile method, a Scrum framework was used to plan and track the development of the project. Scrum follows an incremental approach in which a large project is broken into a series of mini goals called "sprints" (Darwish and Megahed, 2016). These goals were broken down into manageable and trackable tasks for the team to handle over a specified timeframe. Sprints were generally four to six weeks in length for the development of IVAN. During the design and development of IVAN, the team conducted five sprints.

The Scrum framework has three elements: roles, events, and artifacts. The three main roles are the product owner, the Scrum master, and the team. At the end of each sprint, the team received feedback from the faculty advisors (the product owner) to provide the team with an objective view of their progress and performance to date. The team leader (the Scrum master) facilitated the productivity of the team. During the sprint review, the faculty advisors evaluated the progression of the project and offered suggestions to the team as to how and when the team should proceed into the next sprint. The feedback helped the team devise a plan on how to accomplish their intended goals.

The events of the Scrum framework included a daily Scrum meeting, a sprint review, and a sprint retrospective. Daily Scrum meetings were conducted at the beginning and end of each work period. During the daily Scrum, conducted at the beginning of the work period, the team reviewed the current sprint goal and each team member described what he or she planned to accomplish during the work period. Sprints concluded with "sprint reviews," in which the results of the sprint were presented to the Department of Electrical Engineering and Computer Science (EECS) and Department of Systems Engineering (DSE) advisors. This allowed time for the team to reflect on the project progress and incorporate any changes that were needed. USMA's team had five sprints (plus a Sprint 0) which had the goals of conducting a literature review, creating subsystem designs, validating the sensors and subsystems independently, and then finally integrating the system components and algorithms into a fully autonomous robot.

2. Innovations

IVAN is a tracked ground vehicle, pictured in Figure 1, capable of autonomous navigation based on the framework and design of IZZY, USMA's 2018 prototype (Johnson et al., 2018). IVAN's innovations include a physical redesign to optimize movement on sloped terrain, pegged gears to improve traction, and a redesigned computing system capable of machine learning and executing a neural network. The IZZY design was reconfigured so that IVAN would be more compact with a lower center of gravity for improved maneuverability and reliability. This redesign from last year's model allowed the team to create a robot that can operate in more challenging terrain thus meeting the new requirement in the 2019 IGVC for the capability of navigating up and down ramps with gradients of up to 15 degrees. The redesign lowered IVAN's center of gravity which made the robot more stable while navigating sloped terrain.

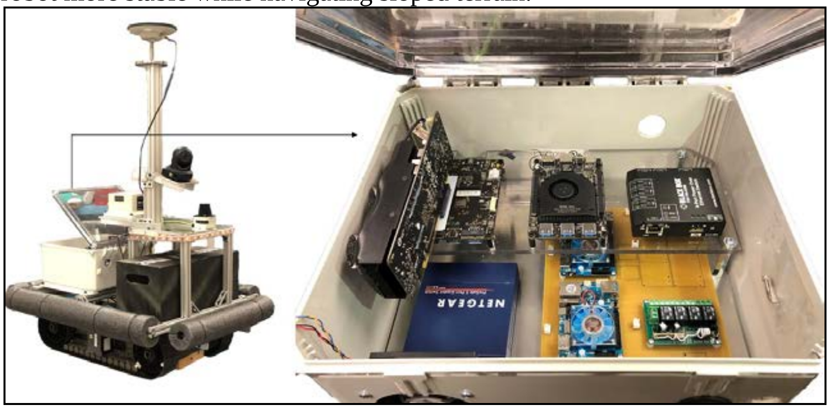

Figure 1. Intelligent Vehicle of Autonomous Navigation (IVAN) and an enlargement of the Computing System

The base platform (robot) shown in the figure is referred to as a GVR-bot. It was originally an iRobot Packbot 510 chassis that was converted the US Army's GVSC to an open system architecture for robotic research and development. The GVR-bot is compatible with ROS. By selecting the GVR-bot as the base platform, IVAN can be easily reproduced on pre-existing military platforms. Last year's USMA team's prototype suffered from track slippage that negatively affected the robot's ability to sharply turn while on the move. The slippage problem was caused by not enough friction (or grip) between the robot's sprockets (i.e., wheels) and its rubber track. White 3D printed pegs, seen in the tracks of IVAN in Figure 1, were designed for the tracks' gears to improve the grip between the wheels and track. The innovative addition to the robot solved the track slippage issue experienced last year.

Another major innovation made in the design of IVAN was the construction of a new computing and control system which processes the sensors' raw data and, through the neural network, makes navigational decisions. The computing box shown in Figure 1 contains a printed computer board (PCB), four single-board computers, two networking switches, and a graphic processing unit (GPU) with Ethernet cables connecting each of these components. Compared to USMA's previous prototype from 2018, IVAN's computing box contains less wiring. This modification to the original design increases reliability of the system and allows for this portion of the robot to be reproduced in a shorter period of time. The new networking configuration and addition of Ethernet-capable sensors allows for faster data transfer and easier monitoring of system subcomponents. The addition of a GPU to the computing platform made it possible to leverage machine learning (i.e., neural networks) for the detection of course's path and avoidance of obstacles. By tele-operating IVAN through a similar obstacle course, the neural network learns from the human operator's examples and develops the capability to self-drive and avoid obstacles.

The final major innovation implemented with the IVAN prototype is inclusion of the CNS-5000 GPS into IVAN. This device is compatible with a TerreStar correction service. TerreStar is capable of providing centimeter positioning accuracy. Compared to the single meter or multiple meter accuracy provided by commercial GPS units of similar size, this device provides a key advantage that will be leveraged in improving the navigational accuracy of IVAN at the 2019 IGVC.

3. Design

At the start of the design process, the USMA IGVC team created a functional hierarchy, as shown in Figure 2, to determine how the team would modify the prototype's mechanical, power, and software design. The functional hierarchy was used to outline what IVAN needed to accomplish and the functions that the system would need to perform. The team decided to use the design from last year's model, outlined in the 2018 IGVC design report, as a basis for the robot and spend a greater amount of time determining the how to best integrate the different sensor data into the decision making algorithm(Johnson et al., 2018). The focus for design work was on tasks 2.0 (Sense Environment) and 3.0 (Calculate Movement) from the Functional Hierarchy in Figure 2 by making smaller physical adjustments while completely revamping the navigational, computing, and obstacle avoidance components. This allowed for focused efforts on innovating and advancing the abilities of the prototype instead of restarting the design process. The next three sections will provide insight into the structural, mechanical, power, and software alterations made to help the robot achieve the functions outlined in Figure 2. The sections provide the final outcomes of improvement and tradeoff analysis and value scoring and costing performed in the design phase.

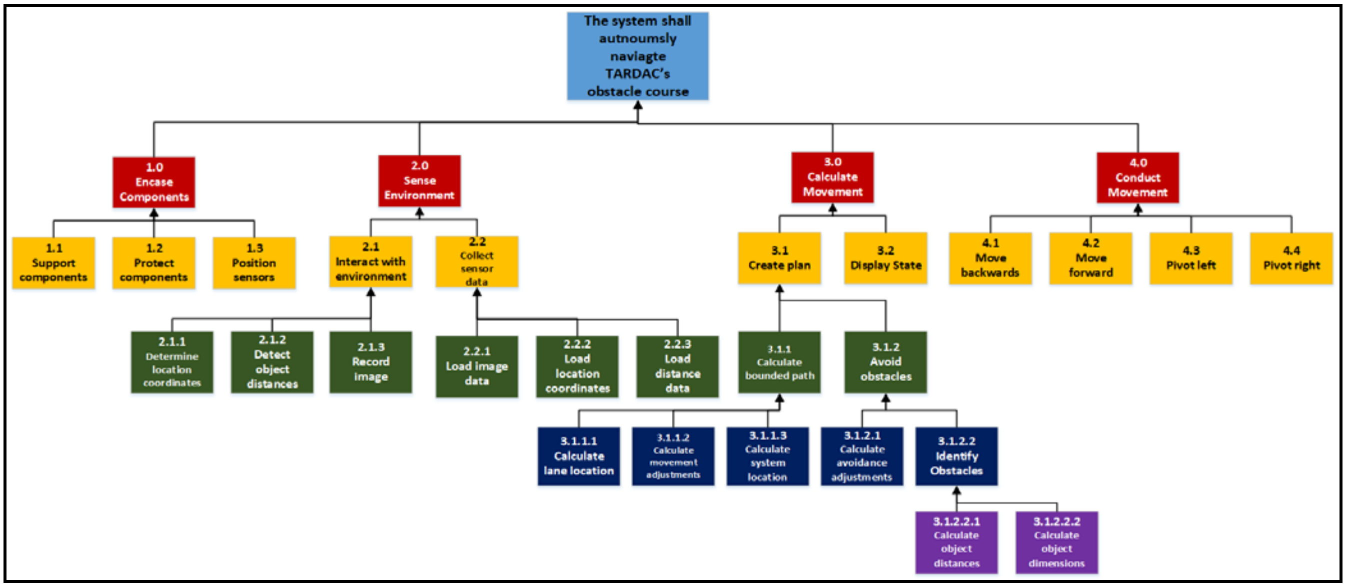

Figure 2. Functional Hierarchy of IVAN

3.1 Structural Modifications

The physical design of IVAN was focused on reducing the physical size of the robot, lowering its center of gravity, and reducing wire clutter. Reducing the physical size of the robot by removing the keyboards, monitor screens, and lowering the center of gravity simplified the design and improved stability. The component box was moved from a vertical position to lying horizontally on the platform of the robot. By moving the component box to a horizontal position, the team lowered the robot's center of gravity and created easier access to the components for troubleshooting purposes. The previous prototype's weather resistant box, the bumper system around the edges of the robot, and the tracked drivetrain platform was maintained as these components did not require any improvements.

The GVR-bot frame is very versatile and effectively encased all components necessary to run IVAN. It uses two tracks with rubber tread and the robot is powered by four military-grade lithium-ion batteries (model: BB-2590) located between the treads on both sides of the vehicle. IVAN's platform use the standard track system and navigational abilities as the GVR-bot base, which is an improvement from previous years' designs. This design enables IVAN to be adapted for use in hazardous environments for military use compared to civilian prototypes. The sensors included in the robot's design include multiple Odroid single-board computers, a CNS-5000 GPS unit, two LattePanda single-board computers, a MSI Geforce GTX 1050Ti, a power over ethernet USB security camera and a small LIDAR mounted on the front of the robot's chassis. These components interface through local switches installed on the robot and meet the IGVC system requirements.

3.2 Mechanical Design

The redesign of the robot's mechanics and frame can be seen in Figures 1 and 3. The framework of the IVAN GVR-bot includes 80/20 aluminum framing to house the payload, computing components, and mounted sensors needed for obstacle detection and avoidance. The robot contains an external LiPo battery, separate from the GVR-bot's batteries, to power the components. This allows the computing components and sensors to be run separate from the system powering the tracks' motors. The 80/20 utilized in the IVAN prototype provides the encasing system to house and position the components providing weather resistance protection and support to the computers and sensors. The decision to make the robot compact adds agility and maneuverability for performance. Housing hardware components in a box with a clear lid provides the necessary weather resistance, maintains the compact design in the rear of the robot, and allows easy access for visual and physical troubleshooting. The GVR-bot is a military-grade robot designed to withstand inclement weather and is one of the reasons why this platform was selected and maintained into this year's prototype. The track system is supported by two wheels inside each of the individual tracks. The suspension system in the GVR-bot includes suspending brackets in the inner side of the track which are adjustable to different operation conditions. Since the competition is located on grass, IVAN's tracks were tested and its parameters adjusted to replicate the competition's conditions. The chassis is water resistant and the hardware components susceptible to water damage are enclosed in a clear plastic weather-resistant housing unit fixed in the rear of the vehicle. This gives the team maximum visibility of hardware around the vehicle for troubleshooting while also keeping the components sheltered, although not completely protected (due to necessary ventilation holes). The mechanical design ensures the robot can physically accomplish the necessary tasks whereas the power design provides the energy to do so.

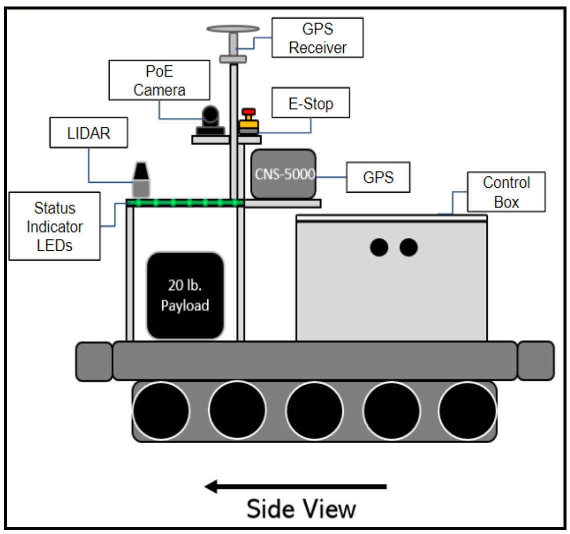

Figure 3. Side View of IVAN

3.3 Power Design

IVAN is powered by four BB-2590/U rechargeable lithium-ion batteries with a 27.2 Amp-hour capacity, and one lithium polymer (LiPo) battery providing 14.8 V at a 20 Ah capacity. The team added the LiPo battery in addition to lithium-ion batteries to extend that operational life. The additional battery allows for the allocation of power capacity to the motor units and the computing components separately. The BB-2590/U batteries power the robot chassis' motors. The chassis design allows for easy access to the interchangeable batteries to simplify replacement. The LiPo battery provides power to the various electronics within the component box, distributed on a printed circuit board. The 14.8 V input power is routed through multiple 12V and 5V regulators to power components directly mounted on the board, such as both Odroid computers and an E-stop receiver, as well as components separately mounted within the box, such as the single-board computers and switches. Using a printed circuit board to distribute power minimizes wiring within the box, which focuses troubleshooting on software rather than hardware.

3.4 Software Design

IVAN's software design leverages ROS to expedite development by facilitating simultaneous work done by team members individually on subsystems while targeting a modular design. The ROS infrastructure uses nodes that can

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concurrently run independent processes. By using ROS, USMA's team benefited from abstraction and did not have to write new multithreaded code. ROS also provides various tools and applications to simulate robot behavior, such as ROS 3D Robot Visualizer (RViz). The ROS repository is an additional core component to ROS that proved helpful in successfully integrating various components that publish or subscribe to various topics to receive messages. This function allows better debugging functionality for quicker implementation process.

4. Conclusion and Future Work

This year's IGVC robot prototype, IVAN, meets the requirements outlined in the IGVC rulebook. Compared to last year's design, IVAN contains several new enhancements. These novel improvements include: a more powerful, yet efficient and compact, computing system that can support autonomous navigation by a neural network; a higher resolution camera and an improved computer vision algorithm; a new obstacle avoidance algorithm for robustly finding open paths using a laser rangefinder; an improved track design that prevents slippage when attempting aggressive (or pivoting) turning maneuvers; a redistributed payload design that lowers the robot's center of gravity; a custom printed circuit board (PCB) for wiring components together and regulating power; and a Lithium Polymer (LiPo) battery used to power the components separate from the GVR-bot's battery power to elongate overall battery life of the robot. IVAN serves as a potential multi-purpose, durable, expandable, technical, and highly capable robot that could be utilized by the US Army GVSC to understand how to better craft robots for the United States armed forces' arsenal that can also conduct mobile computing, surveillance, or payload transportation. The team will continue to refine and improve the design specifications, performance, and autonomous capabilities of the robot up until the date of the competition in June 2019. With the Agile design approach implemented, highly capable components used, and expertise from a multi-disciplinary team, IVAN should be extremely competitive for the IGVC.

Looking forward, future work could be done on the durability of the robot's framework and housing as well as improvements on the payload capabilities. The team was unable to make a more compact, lighter weight, longer lasting, and more powerful prototype that would be beneficial in military settings. IVAN's technical components are designed to be easily replaced with upgraded modern components to expand the computing and processing power of the robot. Improving the durability of the framework while condensing the footprint of the robot itself would make the design more readily applicable for use in combat. Additionally, increasing the ability for IVAN to carry and transport would allow for increased freedom of maneuver for soldiers not carrying as much equipment. Improving these system elements would allow IVAN to be more competitive as a design to be considered for use in the United States Army for reconnaissance, payload transportation, and mobile computing.

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