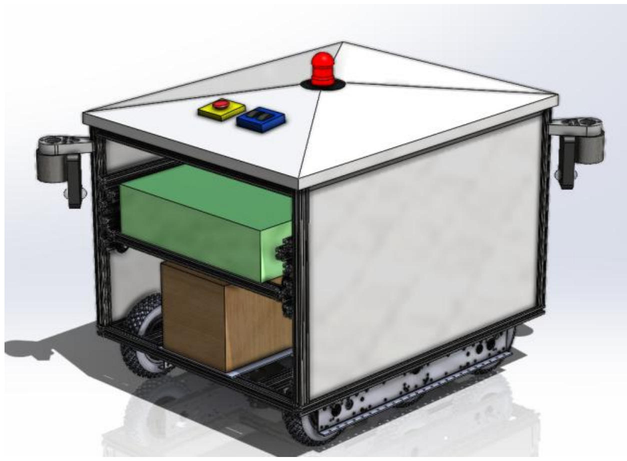
Intelligent Ground Vehicle Competition 2025

Wayne State University

Warrior Robotics

Design Report



SHANTI

I certify that the development of the vehicle, Shanti, described in this report is equivalent to the work in a senior design course. The students of this team have prepared this report under my guidance.

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Date: 15/5/25

Team Members

Board	Software	Electrical	Hardware
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1. DESIGN PROCESS AND TEAM ORGANIZATION

1.1. *Introduction*

Shanti is the Wayne State Warriors Robotics Club's next-generation autonomous robot, engineered from the ground up with completely new mechanical, electrical, and software systems to overcome past limitations and set a new paradigm for modularity, feasibility, and long-term innovation at IGVC 2025. Building on insights from mentors and alumni, *Shanti* embodies a fresh design philosophy aimed to adhere to and exceed IGVC standards with a robust, adaptable, and competition-ready platform.

1.2. *Organization*

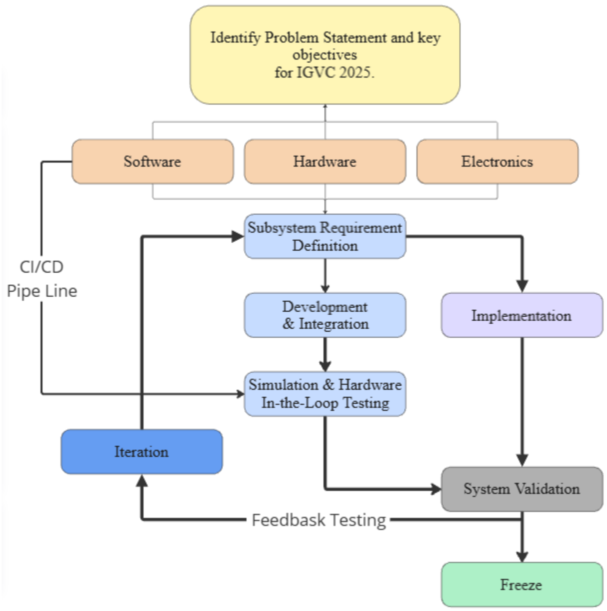

Figure 1: Continuous Integration and Continuous Deployment of Software and Hardware

The team comprises over 25 undergraduate and graduate students from diverse backgrounds, structured into four primary sub teams with clearly defined responsibilities:

- ***Software***: Responsible for autonomous systems development, including core architecture, control logic, and system integration.
- ***Hardware***: Mechanical design and fabrication, focusing on structural integrity, modularity, and environmental resilience.
- ***Electronics***: Embedded systems, power distribution, and hardware-software interface with an emphasis on safety and reliability.
- ***Executive Board***: Strategic direction, cross-functional coordination, project execution and sponsor engagement.

Each subsystem is further split into smaller teams led by a senior board member to facilitate accelerated production of design implementations, this structure enabled continuous alignment, faster decision-making, and a culture of shared innovation across all sub teams.

1.3. *Design Process and Assumptions*

The team follows an Agile development methodology, structured around short sprints, iterative milestones, and subsystem-specific deliverables. Development was divided across software, hardware, and electronics teams, each operating semi-independently under a shared architectural vision. Senior members facilitated subsystem integration and continuous review, ensuring synchronized progress and early risk mitigation.

A Continuous Integration and Continuous Deployment (CI/CD) pipeline was implemented for ROS 2 development as the software was completely rewritten. This approach supported builds, integration, and simulation-based validation. Code was managed via GitHub with enforced branching and review protocols. Only after thorough review did the pull-request to the main branch get approved—it was otherwise blocked.

Hardware and electronics followed synchronized prototyping cycles informed by simulation feedback. Design assumptions were based on prior IGVC conditions, including GPS uncertainty, variable ambient lighting, sensor noise, and non-uniform terrain. These informed decisions on sensor fusion strategies, fail-safe logic, and environmental robustness. A simulation-first workflow using Gazebo enabled early fault isolation and reduced risk before physical testing. As shown in Figure 1, the pipeline progressed through modular planning, implementation, simulation, and feedback-driven refinement. This structured process reduced integration issues and enabled early fault isolation. Over the nine-month development cycle, the team contributed over 3,000 cumulative person-hours, supported by a $20,000 USD budget allocated across component sourcing, prototyping tools, and technical resources.

1. SYSTEM ARCHITECTURE

The robot integrates advanced computing hardware (Lenovo Legion 9i laptop, Arduino controllers), a comprehensive sensor suite (GPS, IMU, Unitree 4D LiDAR, Insta360 camera, temperature sensors, high-resolution encoders), and a robust power system (dual-battery setup with converters and chargers). Reliable communication is ensured through USB and M12 connectors. Safety is prioritized with emergency stop switches, remote disconnect units, solid-state relays, power isolation switches, circuit protection elements (breakers, fuses, diodes), and visual indicators (beacon light).

2.2. *Safety devices*

Our primary safety motivation is to ensure reliable, fail-safe operation in dynamic and unpredictable environments by integrating multi-layered hardware protections that enable immediate shutdown, system isolation, and clear operator awareness—minimizing risk to both the robot and nearby personnel.

1. ***Emergency Stop (E-Stop):*** A latching switch immediately cuts off the control voltage to the solid-state relays, which in turn disables both the main and auxiliary power outputs. This provides a fast manual shutdown method during fault conditions.
2. ***Isolated Power Domains:*** Independent main and auxiliary switches ensure selective energization of Auxiliary and high-power subsystems, enhancing safety during maintenance and startup.
3. ***Circuit Protection:*** Fuses, Diodes, and Thermal-magnetic breakers safeguard critical circuits from overcurrent, short circuits, and stall conditions, reducing fire and hardware failure risk.
4. ***Solid-State Relays (SSRs):*** SSRs offer fast, arc-free switching via semiconductor devices, eliminating mechanical wear and improving EMI suppression.
5. ***Wireless Remote Cutoff:*** A remote disconnect unit enables instant system shutdown from up to 200 feet, providing offboard safety intervention capability.
6. ***Visual Safety Indicators:*** High-luminance LED strobes activate on power-up to indicate live system status and improve operator awareness in active zones.

2.1. *Significant mechanical, power, and electronic components*

Compute	Sensor Suite	Power	Communication	Safety
Lenovo Legion 9i	Movella GPS, IMU	Battery 1 - 12V 100Ah (Propulsion and Electronics)	M12 Cable Systems	E-Stop Switch
Arduino ESP32	Unitree 4D Lidars	Battery 2 - 12V 35Ah (Laptop)	USB	Power Switches
Arduino UNO ATMEGA328P	Insta 360	Boost Converter – 12V to 19V	TCP/IP	Remote Disconnect Units

Roboclaw 2x60A Motorcontrollers	BME280 Temperature Sensors	Buck Converter - 12V to 5V	I2C	Solid State Relay Systems
LinkStar H68K	CIM 260 Hi Resolution Encoders	Battery Charger AC to 2xDC	UART Serial	Circuit Breakers & Fuses & Diodes

TABLE 1: Component List.

2.3. *Significant Software Modules*

Our software stack is containerized into, enabling streamlined integration, isolated development, and reliable system scalability

1. ***Base:*** Implements core kinematics, odometry, and actuator control logic through ROS 2 nodes interfacing directly with drivetrain and feedback systems.
2. ***Simulation:*** Provides a high-fidelity Gazebo environment with URDF/SDF models replicating IGVC terrain features for HIL/SIL validation of autonomous behaviors.
3. ***Perception:*** Integrates 360° LiDAR-camera fusion and custom AI model to generate dense, real-time semantic and geometric understanding of the environment.
4. ***Localization***: Utilizes a cascaded dual-EKF system to fuse RTK GPS, IMU, and encoder data for robust, sub-meter localization with high-frequency state estimation.
5. ***Navigation:*** Leverages a customized Nav2 stack with TEB-based local planning and behavior-tree coordination for dynamic trajectory generation and obstacle avoidance.

2.4. *Integration of significant components and safety devices*

System components are organized across modular enclosures—Power, Electronics, and Laptop Boxes—linked via fused power rails, and USB panel-mounts and hubs for reliable data and power flow. All external sensors powered and connected using either M12 or USB cables. Safety-critical elements such as the E-Stop, SSRs, and Remote Disconnect Units are embedded within the power distribution loop, enabling rapid, system-wide shut down. Circuit breakers, fuses, and diodes provide electrical fault protection at the circuit level. Independent power domains isolate high-current and auxiliary systems, while beacon lights and LED strobes offer real-time system status visibility, enhancing safety.

3. **EFFECTIVE INNOVATIONS**

3.1. *Mechanical*

3.1.1. *Chassis Design and Structural Redundancy*

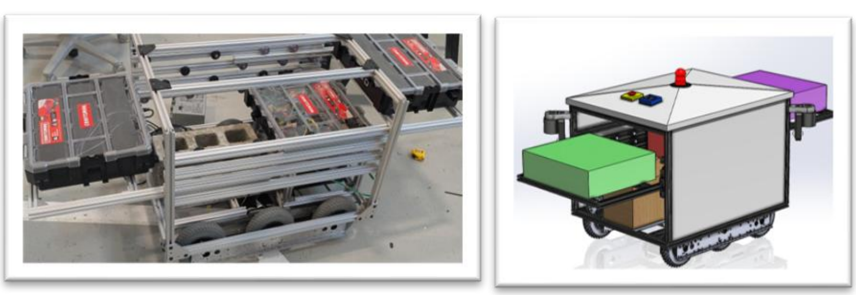

FIGURE 2: Sliding drawer, easy access platform with custom 3D printed shell and waterproof enclosures.

Shanti's frame is built from 1 in X 1 in 80/20 T-slot aluminum extrusions, selected for their modularity, high strength-to-weight ratio (~240 MPa yield strength), and reconfigurability. This design allows for over 40 mounting points and facilitates rapid hardware changes. Load simulations in *SolidWorks* confirmed all critical stress points remained below 60% of material yield during typical terrain interactions, providing built-in redundancy and preserving sensor alignment under dynamic loading.

Criterion	T-Slot Aluminum	Welded Steel	Carbon Fiber Frame	Laser-Cut Sheet Metal	3D-Printed Polymer
Structural Strength	High (Yield ~3500 psi)	Very High (Yield >3600 psi)	Moderate (resin-dependent)	High	Low to Moderate
Weight (kg/m²)	Moderate (~12 kg/m²)	High (~25 kg/m²)	Very Low (~5 kg/m²)	Moderate (~15 kg/m²)	Low (~8 kg/m²)
Assembly Time	Fast	Slow	Very Slow (	Moderate	Fast (if preprinted)
Modularity	Excellent (fully reconfigurable)	None (fixed geometry)	Poor (fixed post-fabrication)	Low	High (if segmented)
Fabrication Tools Required	None	Welding + jigs	Molds, vacuum bag, CNC	CNC/laser cutter	3D printer + post-proc.
Repairability	High	Low	Low	Medium	Medium
Vibration Tolerance	Moderate	High	Low (brittle)	High	Low
Cost per Frame (~1m²)	Moderate ($50–80)	Low ($30–50)	Very High ($200–400)	Moderate ($70–100)	Low ($20–60)
Suitability for Prototyping	Excellent	Poor	Poor	Moderate	High
Finish & Appearance	Industrial/clean	Rugged/raw	High-tech/glossy	Sharp/minimalist	Customizable

TABLE 2. Chassis Material Comparison.

3.1.2. *Sealed Electronics Enclosure*

Core electronics are housed in a CNC-cut IP67 Craftsman toolbox, with all interfaces sealed using marine-grade silicone and compression cable glands rated for −40°C to 100°C. Dual 80 mm fans provide 20 CFM airflow, filtered through PTFE-coated hydrophobic mesh to prevent water and particulate ingress while maintaining internal temperature stability

3.1.3. *ASA Outer Shell and Environmental Shielding*

The outer body uses 3 mm ASA panels, chosen for their UV resistance, thermal stability (−20°C to 85°C), and lightweight durability. In field tests, ASA reflected ~15°C more heat than dark ABS equivalents, improving thermal efficiency. All external cabling is internally routed or sealed through IP-rated conduits, ensuring full ingress protection during outdoor operation.

3.2. ***Electronics***

3.2.1 *Modularity*

Our system features a modular three-box design—Power, Electronics, and Compute—that separates high-current, control, and processing subsystems. Each enclosure is independently serviceable and electrically isolated, enabling hot-swappable upgrades, parallel development, and localized fault recovery. Standardized connectors and dedicated USB/data pathways streamline integration while minimizing cross-interference. This architecture reduces downtime, accelerates debugging, and enhances adaptability across hardware iterations.

3.2.2 *Safety Redundancy*

The robot incorporates multi-layered fault tolerance via hardware and software safeguards distributed across all subsystems. Key safety features include dual-domain power isolation (main/auxiliary), solid-state relays, circuit-level thermal breakers, an integrated Remote Disconnect Unit, and a unified E-Stop loop that cuts power system-wide.

3.3. ***Software***

3.3.1 *Full-Field 360° LiDar-Camera Sensor Fusion*

We implemented a dual-pair fusion system combining a Unitree 4D LiDAR with Insta360 panoramic cameras. This configuration provides real-time, full-surround depth imaging with redundancy, eliminating blind zones and enabling high-fidelity perception for dense obstacle environments without requiring extensive and computationally expensive perception pipelines.

3.3.2. *High Resolution Lane and Pothole Detection*

Custom-trained and fine-tuned model performs pixel-wise semantic segmentation for lanes and potholes under complex lighting conditions to accommodate interjecting yellow parking lanes. Compared to traditional methods, it enables geometry-aware perception and adapts to worn markings and variable surface textures with high recall and precision.

3.3.3 *Digital twin*

Our digital twin environment replicates *Shanti*'s full sensor configuration in Gazebo, including GPS, IMU, LiDAR, and camera feeds. It supports real-time execution of the deployed ROS 2 stack, including behavior trees, path planners, and sensor noise modeling, allowing for pre-deployment validation and rapid regression testing

3.3.4. *Live Web-Based Telemetry and Control*

A fully custom ROS 2-compatible web interface enables live telemetry streaming, node graph visualization, and remote debugging via VPN. It supports real-time diagnostics, command publishing, and sensor inspection from any connected device, dramatically improving system transparency and team-wide observability.

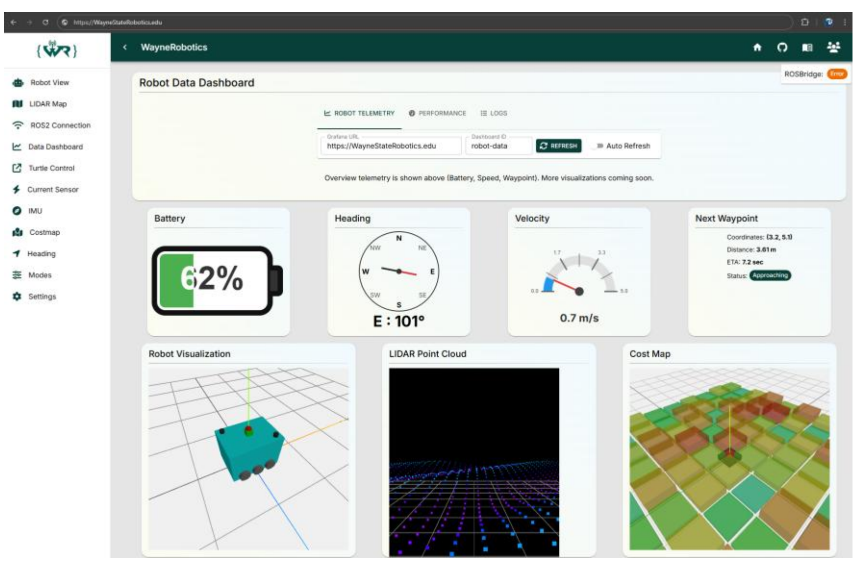

Figure 3: A web interface to the robot that can access much of the data from the robot for visualization and analysis.

3.3.5 *Dual Loop PID Feedback Control*

A dual loop feedback control system enhances the performance and reliability of our position control and odometry. The inner loop (1 kHz) uses motor controllers with pre-gearbox encoders for velocity regulation, while the outer loop (100 Hz) leverages post-gearbox encoders for positional correction via ROS 2. This dual-loop design compensates for gearbox backlash and wheel slip, improving trajectory tracking and odometry accuracy and alleviating issues related to integral overload due to mechanical resistances.

4. DESCRIPTION OF MECHANICAL DESIGN

4.1. *Overview*

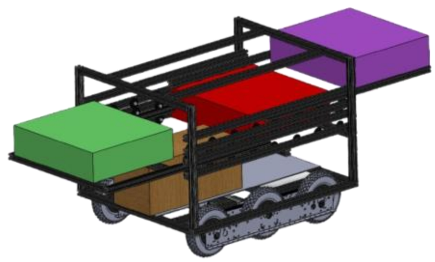

Figure 4: The robot drawer system allows for easy access and modularity

Our mechanical design centers on modularity, serviceability, and field robustness. We design all components using SolidWorks and Siemens NX, enabling accurate modeling, rapid iteration, and precise fit with commercially available hardware. Wherever feasible, we incorporate off-the-shelf components such as the AndyMark drivetrain and IP-rated electronics enclosures to reduce development time without compromising reliability.

4.2. *Structure*

We construct the chassis using 1x1 in. 80/20 T-slot aluminum extrusions, selected for their high strength-to-weight ratio, thermal stability, and reconfigurable nature. The frame follows a T-frame layout, offering structural rigidity while maintaining ease of access. A sliding drawer system houses the computer and electronics modules on independent trays, facilitating tool-less service and internal layout flexibility. The drawer rails also provide secondary structural reinforcement.

4.3. *Drivetrain and Suspension*

Our robot employs a raised-center differential drivetrain based on the AM-14U4 platform, equipped with three 8-inch pneumatic wheels per side. Each side is powered by two CIM brushed DC motors connected via Toughbox Mini gearboxes (9.02:1). This configuration enables center-axis pivoting, improves terrain handling, and achieves a top speed of ~2.5 m/s, while maintaining high torque at low speeds. The pneumatic wheels absorb shocks and maintain traction on uneven surfaces such as ramps or gravel.

Figure 5: The chassis design allows turning at the center of mass and easy traversal of ramps.

4.4. *Significant Design Benefits*

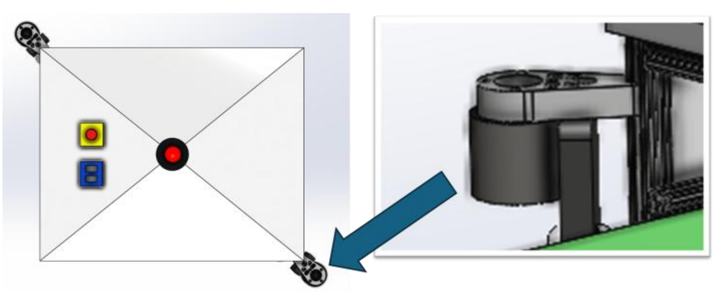

Figure 6: Perception stack mount and their placement within shanti.

We design custom sensor mounts for the Unitree LiDAR and Insta360 panoramic camera, positioned at 45° opposing angles to ensure 360° field-of-view coverage. The mounts are printed in ABS with 40% infill and reinforced to maintain rigidity during motion. Each mount integrates into the T-slot chassis and includes countersunk screw holes for secure attachment and minimal vibrational resonance.

4.5. *Weatherproofing*

We house all electronics in IP67-rated enclosures, mounted on aluminum trays for thermal dissipation and vibration isolation. A custom 3D-printed ASA outer shell, printed at 5 mm wall thickness, provides full coverage against dust, water, and UV exposure. The shell slides securely into the 80/20 grooves and supports mounts for the IP55-rated E-stop, main power switch, and status light. ASA was selected for its UV resistance, impact strength, and thermal durability up to 93°C.

5. **DESCRIPTION OF ELECTRONICS AND POWER DESIGN**

5.1. *Overview*

The robot's power and electronic systems are designed to support robust and efficient operation, integrating dual battery sources and a comprehensive network of components. Both systems incorporate solid-state relays, motor controllers, sensors, and a battery charger, with additional support from an Arduino-based control suite and wireless connectivity. It also emphasizes modular domain separation, low-latency signal routing, and fail-safe power control. Systems are compartmentalized into three enclosures for power management, motor/sensor control, and computing, enabling thermal isolation and independent debugging. All schematics were built using EPlan and underwent a thorough design review to identify and alleviate errors and possible failure scenarios.

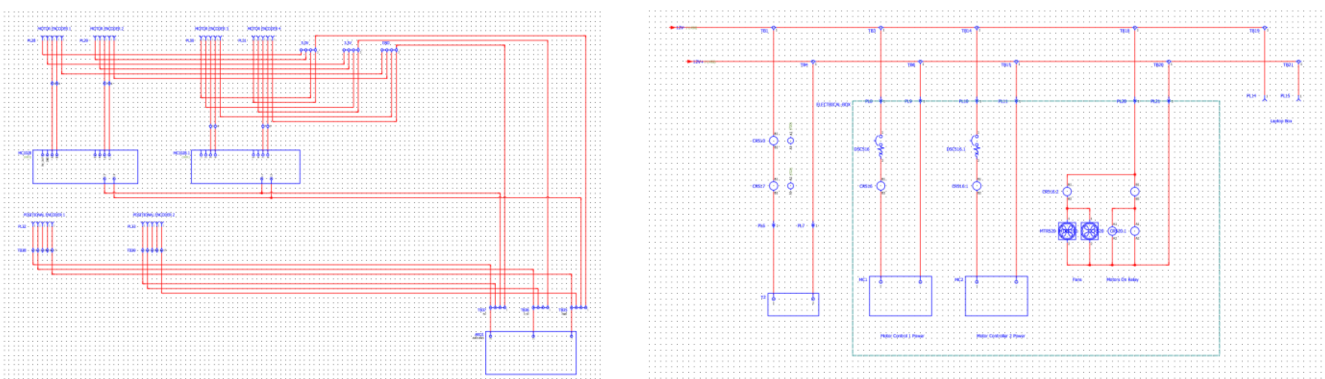

Figure 7: Schematics

5.2. *Description of the Significant Power and Electronic Components*

The system is powered by a 12V 100Ah (1200W) main battery and a 12V 35Ah (420W) auxiliary battery routed through Solid State Relays that are controlled by switches, safety signals, and software. A 12V to 5V Buck Converter steps down voltage for electronics and switching circuits, while a 12V to 19V Boost Converter powers the laptop. High current 12V connections power the motor controllers and motors through 80A panel-mount connectors. Low current 12V connections are distributed through 20A panel-mount connectors to power miscellaneous items, such as fans, LiDARs, and a wireless router. Encoders utilize custom-made M12 5-pin cables leading to panel-mounted connectors for power and data transfer to/from microcontrollers. An ATMEGA328P microcontroller with attached relays monitors temperature and controls fans, safety light, and motor power. The charging system features a single 120VAC source to recharge both batteries simultaneously. All connections between panel-mount connectors are routed through Wago snap connectors to enhance serviceability. Wago connectors are also used in conjunction with bus bars for power distribution. Every wire termination is ferruled for stronger connections and thermal management.

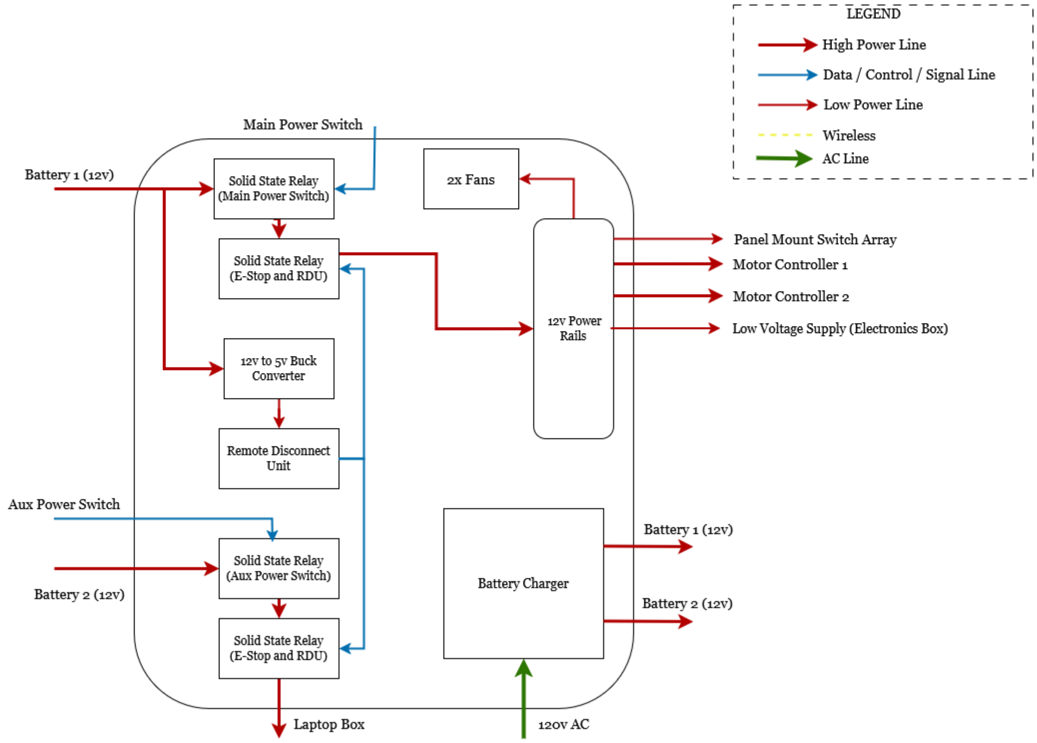

Figure 8: Power Distribution Box

5.3. ***Power Distribution System Capacity, Max. Run Time, Recharge Time, Safety***

The power distribution system utilizes two batteries, providing 1200W main power and 420W auxiliary power. The system supports high-power circuits through 60A circuit breakers, staying within the 80A limits of the power connectors and in-line Solid State Relays. Low-power circuits are protected using in-line fuses. M12 connectors are rated up to 5A, well below the power draw of each device. All internal power distribution circuits were analyzed and tested to ensure that they do not exceed the 25A rating of the Wago snap-in connectors.

Under typical load conditions, the main system draws approximately 1200W, yielding a maximum runtime of about 1 hour. The laptop subsystem, drawing 210W, can operate independently for up to 2 hours. When both systems run concurrently, the total available runtime is approximately 1 hour. Battery recharge times are estimated at 10–12 hours for the 100Ah battery and 4–5 hours for the 35Ah battery using standard chargers.

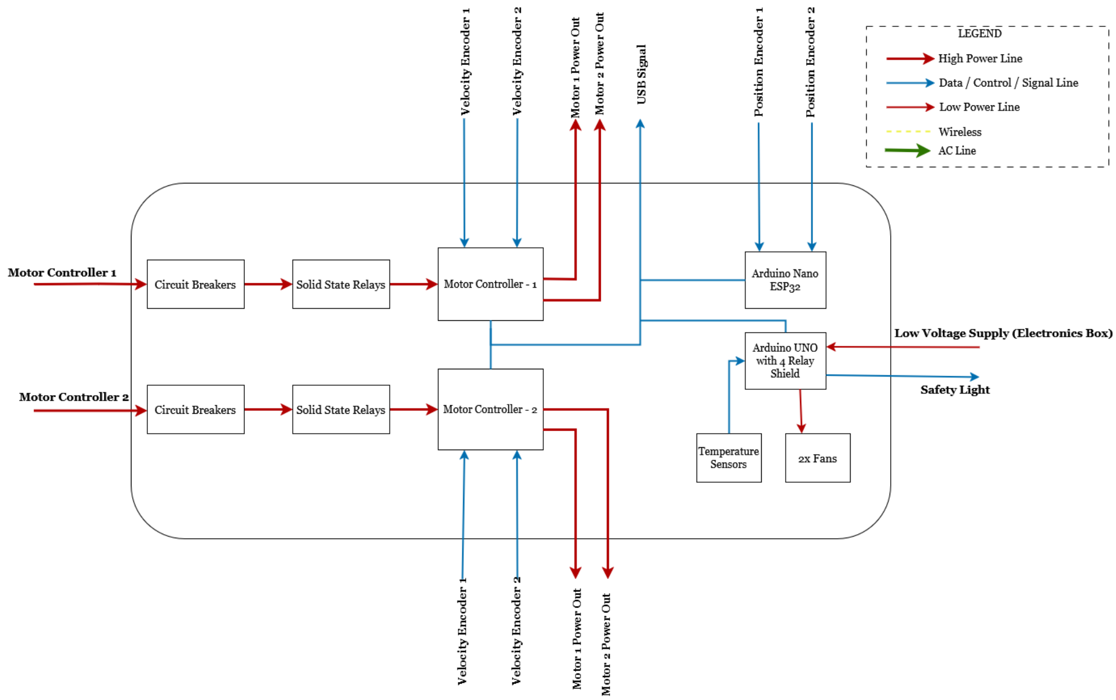

Figure 9: Electronics Box

5.4 ***Electronics Suite, Including Computers, Sensors, Motor Controllers***

The system uses a laptop connected via USB panel mounts and hubs to two RoboClaw 2x60A motor controllers (60A peak per channel), two LiDARs, two Insta360 cameras, and a GPS/IMU. Four pre-gearbox CIM encoders provide motor velocity feedback via 2-wire quadrature to the RoboClaws, while two post-gearbox CTR encoders send positional data to an ESP32 microcontroller. A LinkStar H68K router enables remote debugging and connectivity. Safety systems include an ATMEGA328P microcontroller with a 4-relay shield: it controls six fans, a safety light, and motor power enable/disable, while monitoring temperature via a BME280 sensor using bit-banging I²C.

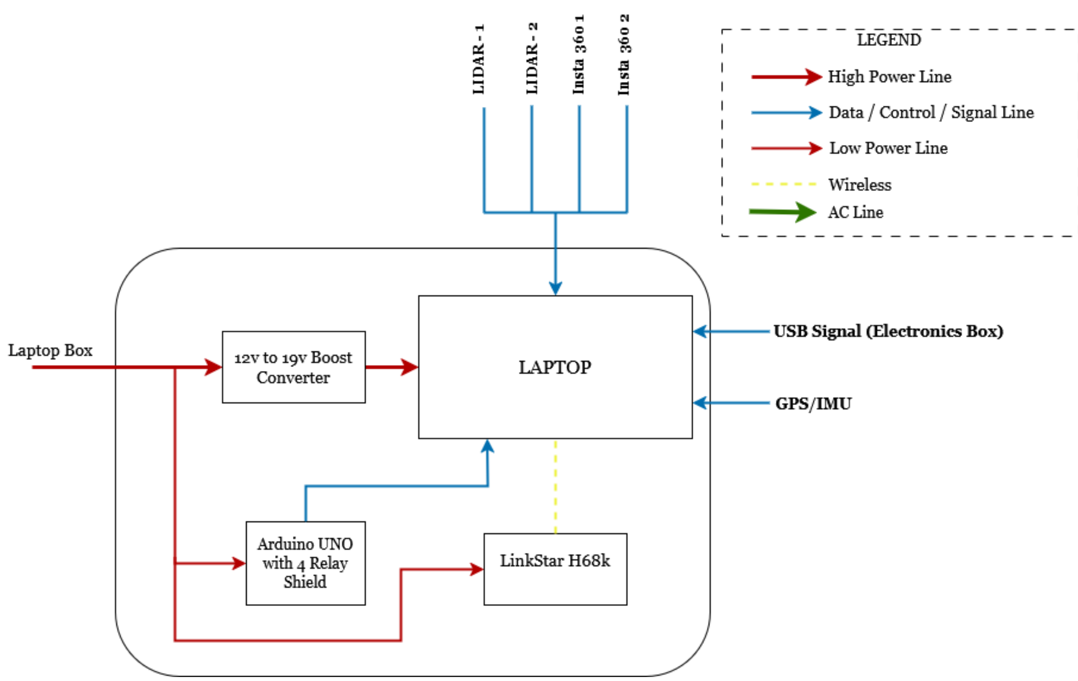

Figure 10: Laptop Box.

5.5 **Mechanical and Wireless ESTOP Systems**

The mechanical E-Stop system is integrated into the solid-state relays, allowing immediate power cutoff to critical components like the motor controllers and fans through Solid State Relays in series to the main and auxiliary power switches. Normally open relays on normally closed E-Stop switches ensure that any damage to the safety circuits causes an immediate shutdown. The wireless E-Stop is facilitated by the Remote Disconnect Unit (RDU), enabling remote shutdowns up to 200ft line-of-sight distance.

6. **DESCRIPTION OF SOFTWARE SUITE**

6.1. ***Overview***

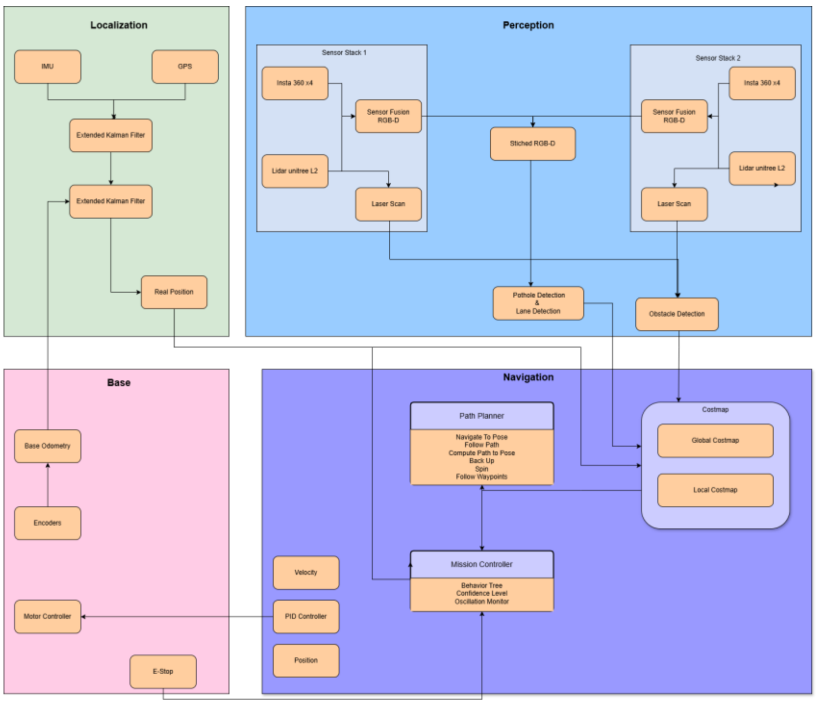

Figure 11: Software Architecture

Our software stack is built on ROS 2 Humble, structured into five core modules: Base, Perception, Localization, Navigation, and Simulation. Each module is encapsulated in a ROS 2 package group with independent bring up files. Lifecycle nodes, DDS middleware, and Python launch scripts allow for deterministic initialization, modular debugging, and fault-tolerant auto-recovery. The stack supports simulation and real hardware through a unified interface, ensuring consistency across development and deployment.

6.2. ***Perception Pipeline***

The robot employs a dual-sensor architecture that fuses Insta360 X4 equirectangular imagery with Unitree L2 4D LiDAR using a custom RGB-D fusion node aligned in a shared polar coordinate frame, enabling real-time 360° scene reconstruction. Lane and pothole detection is performed by a fine-tuned model trained on annotated spherical data, producing binary masks that represent environmental features.

These masks are converted into RGB-D point clouds and integrated into the local costmap for obstacle inflation. A diagonally mounted dual-sensor configuration, with 270° coverage per unit, ensures complete 360° perception and maintains operational redundancy in the event of individual sensor failure.

6.3. ***Scene Understanding and Localization***

Environmental understanding is achieved through layered costmaps, where a global costmap captures static features and a local costmap integrates real-time sensor data using a rolling buffer. Localization relies on a dual-stage EKF: the The first EKF node (ekf_filter_node_odom) combines wheel encoders + IMU to provide precise, short-term local positioning, reducing odometry drift; the second stage fuses RTK GPS and the previous EKF output for a corrected global pose. The GNSS system provides 1m CEP, with a sub 10cm accuracy using RTK. The IMU offers 0.007 °/s/√Hz noise density and 8 °/hr bias stability, providing precise heading data and supporting robust localization in degraded or occluded GNSS condition.

6.4. *Path Planning and Control*

The navigation stack combines SMAC Hybrid-A* for global planning and Regulated Pure Pursuit for local control, managed by the Nav2 plug-in library. This behavior-tree-based mission controller handles path execution, recovery, and mode switching. Trajectories are adapted in real time using dynamic costmaps and semantic inputs from lane and pothole detection, with obstacle encounters triggering re-planning or fallback behaviors.

6.5. *Execution and Mode Switching*

The robot operates in three autonomous modes: GPS Waypoint Mode (default), Lane Following Mode (engaged when segmentation confidence exceeds a predefined threshold), and Recovery Mode (triggered by deadlock, sensor dropout, or path obstruction). Trajectory execution is governed by the outer loop positional PID controller through built in Nav2 mechanisms.

6.6. *Simulation and developer tools*

Our Gazebo-based digital twin replicates all sensors with noise modeling for SIL/HIL testing and parameter tuning. A Next.js and React dashboard interfaces via ROSBridge, providing real-time telemetry, video (WebRTC + GStreamer), and diagnostics. Secure access is managed through a Tinc VPN and cloud reverse proxy, enabling remote monitoring and control.

7. CYBERSECURITY ANALYSIS

7.1. *Framework Overview*

We adopt the NIST Risk Management Framework (RMF) to assess, mitigate, and continuously monitor cyber risks across the robot's lifecycle. RMF includes:

1. ***Prepare:*** Define objectives, threats, and resource constraints
2. ***Categorize:*** Assess CIA impact (Confidentiality, Integrity, Availability)
3. ***Select:*** Tailor NIST SP 800-53 controls based on system category
4. ***Implement:*** Deploy controls (e.g., encryption, watchdogs, port lockdown)
5. ***Assess:*** Test control performance and threat resilience
6. ***Authorize:*** Determine system readiness for deployment
7. ***Monitor:*** Continuously log, review, and respond to new threats

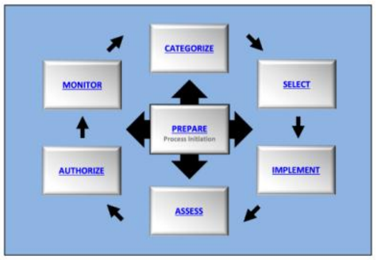

Figure 12: Risk Management Framework

7.2. *Threats and Impacts*

Subsystem	*Threat*	*Description*	*Conf.*	*Integ.*	*Avail.*	*Overall*
Navigation	GPS Spoofing	Injects false GNSS signals to mislead localization	Low	High	Moderate	Moderate–High

	Odometry Fraud	Tampering causes localization drift	Low	High	Moderate	Moderate–High
Perception	LiDAR Replay Attack	Replays past scans to confuse obstacle detection	Low–Mod	High	High	High
	Camera Optical Interference	Laser or flashlight disrupts vision model	Low	High	Mod–High	High
System	Version Control Breach	Credential theft via SSH or token	High	High	Moderate	High
	USB Injection	Malicious firmware overwrites via physical USB	Mod–High	High	Mod–High	High
Hardware	PCB Probing	Physical access to internal data lines	High	Mod–High	Low–Mod	Mod–High
	Power Glitching	Transient voltage drops to disrupt MCU	Low	High	High	High
	EMI Attack	Electromagnetic disturbance to sensors or comms	Low	High	High	Low–High
Communication	Firewall Spoofing	Wi-Fi spoofing to impersonate team nodes	High	Mod–High	Moderate	Mod–High
	DDoS (ROS Topic Flooding)	Overloads DDS middleware or disrupts control loops	Low	Low	High	Low–High

TABLE 3: High impact threat containment.

7.3 ***High-Impact Threat Controls (NIST SP 800-53)***

Threat	*Control (ID)*	*Implementation*	*Test Method*	*Expected Outcome*
GPS Spoofing	SC-19, SC-23	Multi-sensor fallback (IMU/LiDAR) + location sanity checks	Inject false GPS in sim; verify fallback engagement	Maintains accurate pose or triggers alert
Odometry Fraud	SC-16	Redundant fusion (IMU cross-checks); ROS topic validation	Inject noise in encoder; compare with IMU	Detects and flags inconsistency
LiDAR Replay	SC-12	Timestamp validation; cryptographic scan signing	Replay old scans (rosbag); check for temporal inconsistency	Scan discarded or alert raised
Camera Interference	SI-13	Adversarial training; fail-safe behavior tree fallback	Flash laser; assess segmentation model confidence	Safe fallback triggered under degraded vision
USB Injection	SC-41	Disable USB ports; signed firmware validation	Plug in rogue USB payload	Device ignored or blocked
Credential Theft	IA-7	Enforce strong authentication + 2FA; secrets manager	Simulate brute-force login / key theft	Unauthorized access blocked
Power Glitching	PE-20	Use voltage supervisors +	Induce dip; observe MCU	Graceful reset or recovery

		brownout recovery logic	watchdog trigger	
EMI Attack	PE-14	EMI shielding, twisted pairs, conformal coating	EMI gun test at control lines	No loss of function; EMI within bounds
DDoS (ROS Flooding)	SC-5	DDS rate limiting; rogue topic detection; publisher throttling	Flood topics; observe CPU/memory utilization	System suppresses overload, control loop preserved

TABLE 4: High impact threat containment.

8. ANALYSIS OF COMPLETE VEHICLE

8.1. Lessons Learned

Through the nine-month development cycle of Shanti, several key lessons emerged. Foremost was the importance of early subsystem isolation and simulation validation. Early-stage hardware and software development in silos led to integration delays, which were later mitigated through weekly integration reviews and a CI/CD simulation pipeline. The team also learned the critical role of environmental shielding and thermal management, as field tests revealed overheating risks that were mitigated through vented enclosures and improved airflow designs. Additionally, we observed the necessity of clear interface documentation and power domain separation to reduce debugging time and prevent component damage during hot swaps.

8.2. Failure Points and Mitigations

- **Encoder Redundancy**: Motor controller encoder failures emerged as a key risk. To mitigate this, each motor controller is paired with its own encoder, allowing us to mirror data if one fails, ensuring continued odometry feedback.
- **Battery Switchover**: Unanticipated brownouts were observed when switching between charging and operation. We resolved this by introducing soft-start circuitry and battery voltage supervision logic.
- **USB Communication Dropouts**: Extended runs revealed intermittent USB disconnects. These were addressed by switching to industrial-grade cables with EMI shielding and using powered USB hubs for regulated signal integrity.

8.3. Safety, Reliability, and Durability

Safety was embedded from the outset, with solid-state relays, circuit breakers, and redundant E-Stop systems forming a multi-tiered protection architecture. We prioritized modularity and electrical isolation to improve serviceability and prevent cascading failures. All enclosures are IP-rated, thermally managed, and vibration-dampened to support extended outdoor operation under variable weather. Real-time telemetry enables live monitoring of critical diagnostics like temperature, power, and CPU load, allowing preemptive interventions.

8.4. Hardware Failure Points and Mitigation at Competition

- **Motor Controllers**: Dual-motor configuration per side allows partial drive in case of single controller failure.
- **Cooling Systems**: Monitored via Arduino-controlled relays; failures trigger thermal alerts and fallback behavior to reduce load.
- **Power Switches and SSRs**: Each is rated above expected draw and tested for thermal derating; fuses provide final-layer cutoff.
- **Communication Links**: LinkStar H68k supports LTE fallback; in case of wireless E-Stop failure, mechanical E-Stop remains active.

9. **UNIQUE SOFTWARE SENSORS AND CONTROLS FOR AUTONAV**

9.1. ***Custom AI Pipeline for Lane Detection***

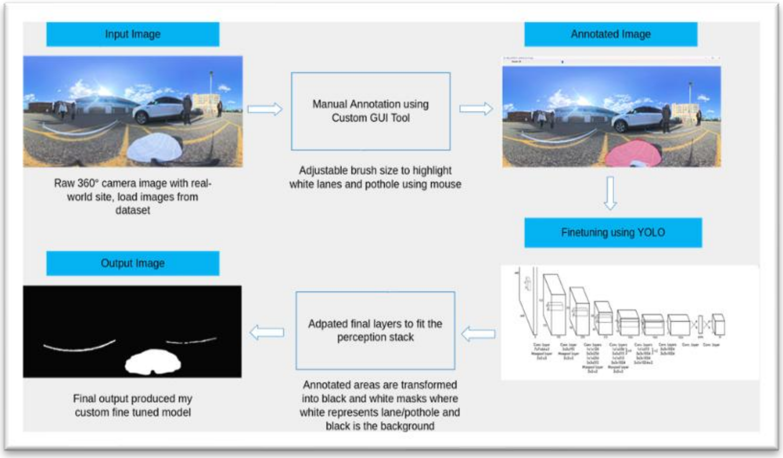

Figure 13: Complete pipeline for finetuned lane segmentation model.

Due to prior failures from lighting variation, 360° distortion, and intersecting yellow lane lines, we developed a custom pipeline with data collection, software tool to generate pixel-level ground truth from Insta360 images. The dataset was used to fine-tune a YOLO-based segmentation model, improving lane and pothole detection under complex visual conditions. This pipeline enabled robust training directly in the equirectangular domain, enhancing model resilience to glare, shadows, and geometric distortion.

9.2. ***IGVC Map Recreation***

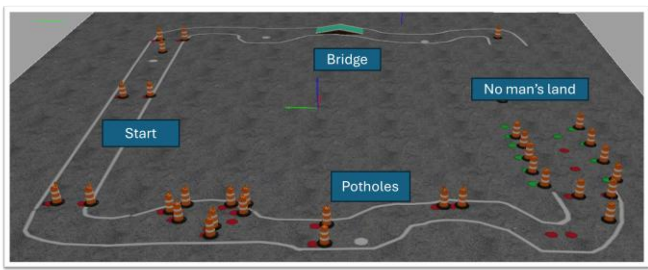

Figure 14: A complete course was created in Gazebo. It included lanes, potholes, and a ramp.

We recreated the IGVC course in Gazebo to enable hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing of our full autonomy stack. The simulation environment includes lane markings, cones, potholes, and elevation features such as bridges.

Our ROS 2-based software runs identically in simulation, interfacing with simulated GPS, IMU, LiDAR, and camera feeds to validate localization, perception, and planning modules under realistic conditions. This pipeline allowed us to test system-level integration, tune sensor fusion parameters, and validate behavior trees and control logic prior to field deployment. In the simulator below, the system navigates to GPS locations. The sensors (IMU, Odom and GPS) are appropriately infused with covariance matrices to simulate error.

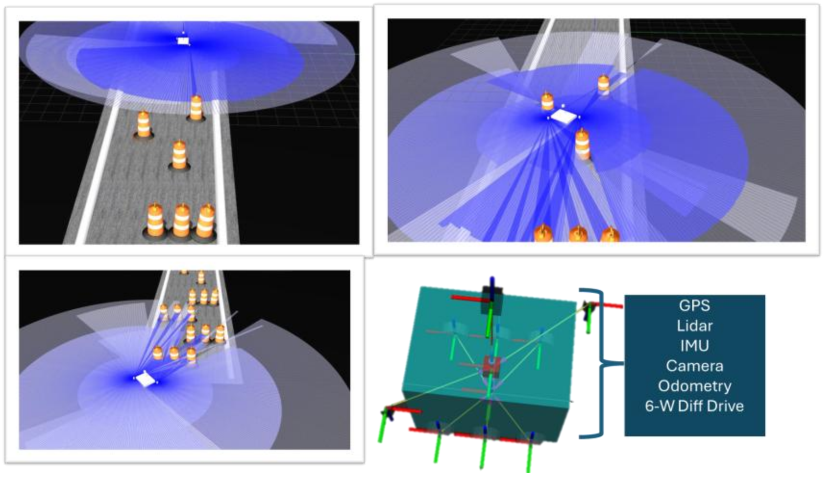

Figure 15: Full Sensor stack integrated digital twin showcasing 360-degree perception capabilities.

10. INITIAL PERFORMANCE ASSESMENT

Shanti was tested extensively to establish initial performance metrics under varying conditions to validate its system level reliability and base line operating conditions.

Max Speed	5.3 mph
Max Acceleration	3.09 m/s^2
Battery 1 Life (main)	1 hr, 10 min.
Battery 2 Life (aux)	2 hr, 30min.
Localization Accuracy	0.1 meters
Obstacle Detection Distance	0.2 to 30 meters
Reaction Times	10 Hz

TABLE 5: Performance Assessment