An Integrated Edge-AI Architecture for Unstructured Off-Road Navigation

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Abstract. Achieving autonomous navigation in mobile robotics requires the tight integration of perception, planning, and control within a unified on-board system. In off-road environments, fully closing the loop on-board with limited computational resources remains challenging because environmental uncertainty and terrain irregularities substantially raise the computational complexity of the required perception and control pipelines. This paper presents a cost-effective yet high-performance Unmanned Ground Vehicle (UGV) designed to bridge the gap between limited educational robots and expensive industrial platforms. The system adopts a dual-layer architecture in which an NVIDIA Jetson module executes neural components and the ROS2 Nav2 stack, while a dedicated real-time controller manages low-level locomotion. The two layers communicate over a CAN bus, ensuring robustness to electromagnetic interference and predictable communication latency. The platform is validated through an outdoor off-road navigation campaign involving trajectories with increasing geometric complexity. The experimental study shows the suitability of the proposed system for systematic evaluation of autonomous navigation performance in realistic off-road conditions.

Keywords: Off-Road Navigation · Unmanned Ground Vehicle · Edge AI · Autonomous Robotics · Real-Time Control

1 Introduction

Autonomous navigation in outdoor environments requires the integration of perception, localization, planning, and control within a fully on-board robotic system. Although autonomous mobile robots are widely adopted in structured indoor domains such as warehousing and intralogistics [4,2], outdoor ground navigation remains more challenging due to less predictable operating conditions, localization uncertainty, and disturbances affecting trajectory execution.
A further limitation concerns the availability of suitable research platforms. High-end UGVs provide robust mechanics and mature software support, but

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their cost may limit accessibility and reproducibility. Conversely, low-cost educational robots are typically designed for indoor use and often lack the sensing, computation, and mechanical robustness required for autonomous outdoor experiments [15]. This creates a practical gap between affordable educational platforms and expensive industrial-grade systems.

This paper presents MiviaRover , an affordable and open UGV platform conceived as a reproducible testbed for outdoor autonomous navigation. The platform executes a complete ROS 2-based navigation stack on board and is experimentally validated in an outdoor paved scenario through autonomous trajectory-following tests. The results demonstrate the feasibility of using MiviaRover as a compact experimental platform for studying localization, planning, and control in field robotics. Project resources and a video demonstration are available at `https://github.com/mivia-rover-nav2/mivia_rover.git` and `https://youtu.be/Nxt2PsCFSNA`.

2 Related Work

Research platforms for mobile robotics span from low-cost indoor robots to rugged UGVs for field deployment. Indoor systems such as the delivery robot proposed in [11] and the ROS 2-based platform in [12] provide accessible testbeds for navigation, mapping, and embedded control. Similarly, PlatROB [1] emphasizes modularity and educational flexibility through interchangeable drive configurations. However, these platforms are mainly intended for structured indoor environments and provide limited robustness for outdoor autonomous navigation.

Conversely, field-oriented platforms are generally more capable but less accessible. Rakshak [5] adopts a tracked configuration for hazardous environments, while the ROS 2-based UGV in [9] is derived from a commercial electric ATV for agricultural operation. These systems offer stronger outdoor capabilities, but their cost, scale, or mechanical complexity limit reproducibility in typical research and educational contexts.

More generally, wheeled, tracked, legged, and hybrid UGVs exhibit different trade-offs between efficiency, terrain adaptability, mechanical complexity, and cost [7]. Wheeled platforms such as SMSS [13] favor efficiency and payload capacity, tracked systems such as TALON [6] improve obstacle negotiation, legged robots such as ANYmal [8] provide high terrain adaptability, and hybrid solutions such as Shrimp [14] seek intermediate mobility through passive adaptation.

This literature highlights a gap between affordable indoor-oriented robots and expensive ruggedized field platforms. Few systems combine accessibility, onboard computation, outdoor sensing, compact form factor, and real-time low-level control within a reproducible architecture. The proposed MiviaRover addresses this gap as an open and cost-conscious UGV platform for outdoor autonomous navigation experiments.

3 The proposed robotic architecture

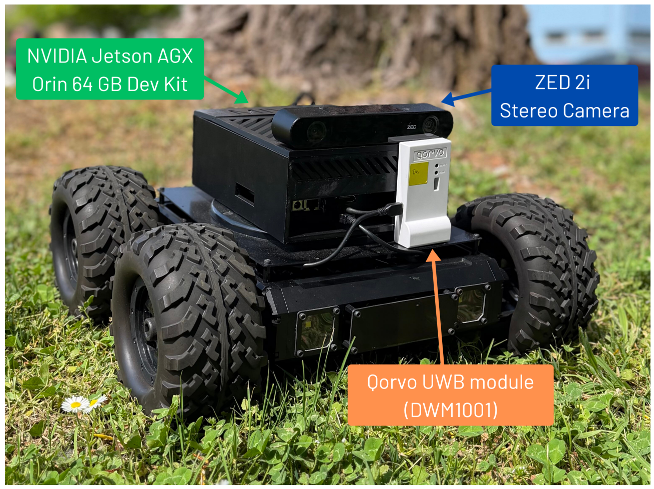

Fig. 1: The MiviaRover prototype used in the outdoor experimental campaign.

The MiviaRover (see Fig. 1) is built upon the Lynxmotion Rugged Rover chassis configured in a differential-drive layout, with four wheels independently driven by brushed DC motors supporting speeds up to 160 RPM and commanded via PWM. Its open mechanical structure served as the basis for a ground-up hardware and firmware design, deliberately avoiding off-the-shelf embedded solutions in favor of a purpose-built control architecture tailored to off-road autonomy. The resulting hardware organization is summarized in Fig. 2. The low-level controller runs on an STM32F767ZI microcontroller, chosen for its hardware floating-point unit and real-time capabilities, hosted on a custom PCB that integrates motor drivers, power management, and sensor interfaces into a single board.

3.1 Sensor Set

The platform is equipped with a heterogeneous sensing suite supporting state estimation, environment perception, and absolute localization through complementary modalities. Proprioceptive sensing relies on the 9 DoF IMU embedded in the Stereolabs ZED 2i and on 48-CPR quadrature encoders integrated on each motor shaft, providing high-rate wheel odometry and short-term egomotion estimates that remain consistent during fast transients and on locally unstructured terrain. Exteroceptive perception is primarily provided by the stereo camera, whose 120 mm baseline and onboard depth sensing supply dense geometric information together with synchronized RGB observations, representing the main source of local mapping, and vision-based learning modules. Absolute positioning is supported by an Ultra-Wideband localization system based on the Qorvo MDEK1001 development kit, whose nodes can be configured as anchors or tags within a scalable real-time setup, providing drift-bounded global position updates that complement the locally continuous but drift-prone proprioceptive estimate.

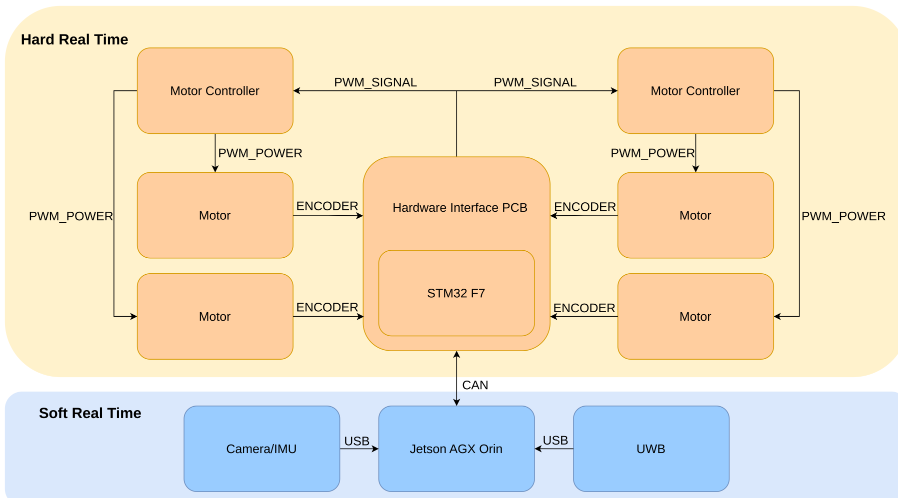

Fig. 2: High-level physical view of the MiviaRover UGV hardware architecture. Hard real time hardware (orange) executes time-critical functions, including motor actuation and encoder acquisition, while the Jetson AGX Orin handles high-level perception and decision-making tasks under soft real-time constraints (blue). The two layers communicate via CAN bus, and external sensors are interfaced through USB.

3.2 Software and Firmware Stack

The high-level software stack runs on the Jetson AGX Orin as a modular ROS2 architecture, encompassing sensing, perception (including ground/non-ground segmentation of the camera point cloud via Patchwork++ [10]), EKF-based localization fusing wheel odometry, IMU, and UWB measurements, and autonomous navigation built on a domain-adapted Nav2 configuration. The embedded firmware, hosted on the STM32F767ZI under a `FreeRTOS` kernel, acts as the real-time execution substrate closing the loop between high-level autonomy and electromechanical actuation: four independent PID regulators, with actuator saturation and anti-windup clamping, track per-wheel RPM references at 200 Hz and drive the PWM outputs accordingly, while a conservative fail-stop policy disables interrupts, deasserts the motor relay, and forces commands to zero on any unrecoverable error. Communication between the two layers is realized through ROS2 Control over a CAN bus, formalized by a DBC file that defines the software–firmware boundary as an explicit, versionable communication contract.

4 Evaluation

This section presents the experimental validation of MiviaRover in an outdoor paved scenario. The experiments are designed to assess the path-following capability of the complete onboard navigation stack, including localization, planning, and control, during autonomous trajectory execution. The paved surface provides a repeatable outdoor setting in which the effect of the integrated system can be evaluated without introducing additional variability due to highly compliant or irregular terrain.
Path-following performance is quantified through the Cross-Track Error (CTE), defined as the minimum Euclidean distance between the estimated robot position $\mathbf{p}(t) \in \mathbb{R}^2$ and the reference path $\mathcal{P}$:

$$e(t) = \min_{\mathbf{q} \in \mathcal{P}} \|\mathbf{p}(t) - \mathbf{q}\|_2 . \tag{1}$$

For each run, we report the mean CTE $\bar{e}$ and maximum CTE $e_{\max}$:

$$\bar{e} = \frac{1}{T} \sum_{t=1}^{T} e(t), \qquad e_{\max} = \max_{t \in \{1,\dots,T\}} e(t). \tag{2}$$

4.1 Experimental Setup

Experiments were conducted outdoors on a paved stone-tile surface within a $4\,\mathrm{m} \times 6\,\mathrm{m}$ obstacle-free rectangular map. The reference frame is placed at the bottom-left corner, while absolute localization is provided by a UWB system with four anchors positioned at the map corners and one tag mounted on the robot, as shown in Fig. 3. Two reference paths were considered: a circular trajectory with radius $r = 1\,\mathrm{m}$, used to impose continuous curvature and heading variation, and a 4 m rounded-rectangle trajectory with 0.5 m corner radii, combining straight segments and curved transitions. The robot follows the reference paths using the *Dynamic Window B* (DWB) controller, the ROS 2 implementation of the Dynamic Window Approach [3]. Two configurations are compared, differing only in the maximum linear velocity: Setting A uses 1.5 m/s, while Setting B uses 0.6 m/s. The remaining parameters are fixed across all runs, with linear and angular acceleration limits of $2.5\,\mathrm{m/s^2}$ and $3.2\,\mathrm{rad/s^2}$, respectively, `vy_samples`=4, and `sim_time`=1.2 s.

Fig. 3: Paved outdoor experimental setup with four UWB anchors placed at the corners of the $4\,\text{m} \times 6\,\text{m}$ test area.

4.2 Results

The two reference trajectories were executed on the paved surface using the DWB configurations described above. For each trajectory, we report the reference path overlaid with the executed path estimated by the EKF, together with the corresponding CTE profile computed according to Eq. (1). Figure 4 shows

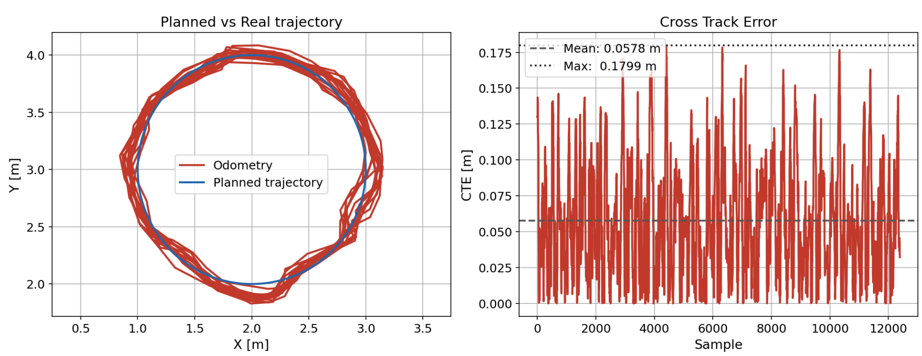

Fig. 4: Path-following result on the circular trajectory over the paved surface. The desired path is shown against the EKF-estimated executed path, together with the corresponding CTE profile over time.

the result obtained on the circular trajectory, which continuously excites lateral tracking and heading variation. The executed path remains close to the reference, indicating that the onboard localization, planning, and control pipeline can sustain curved trajectory execution in the outdoor paved scenario. The CTE profile highlights the main deviations along the run and provides a quantitative measure of the tracking error. Figure 5 reports the result on the rounded-rectangle tra-

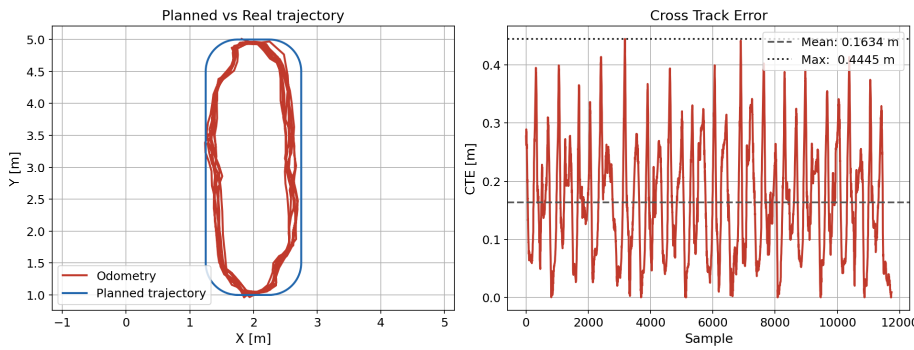

Fig. 5: Path-following result on the rounded-rectangle trajectory over the paved surface. The desired path is shown against the EKF-estimated executed path, together with the corresponding CTE profile over time.

jectory, where straight segments and curved transitions are executed within the same run. The robot follows the reference path without loss of alignment, showing that the proposed platform can handle both linear tracking and curvature transitions under the tested outdoor conditions.

Overall, the results confirm that MiviaRover can execute the complete ROS 2 navigation stack fully on board and follow planned trajectories in a repeatable outdoor paved scenario. The reported CTE values provide a compact quantitative characterization of the tracking performance and support the use of the platform as an experimental testbed for autonomous ground navigation.

5 Conclusion

In this work, the MiviaRover platform has been introduced and made publicly available as a cost-effective system designed for the testing of autonomous navigation algorithms in unstructured off-road environments. The navigation stack has been evaluated across different scenarios, validating the system's capabilities while exposing the inherent limitations of the adopted architecture. In particular, the local planners require careful, context-specific parameter tuning in order to accomplish the assigned mission successfully. This highlights a fundamental tension in off-road autonomous navigation: the dependence on operationally-specific parameterization is at odds with the generalizability requirement that any truly autonomous system must satisfy. A robot deployed in unknown environments cannot rely on a configuration optimized a priori, yet it is precisely in such contexts that autonomy becomes an indispensable requirement.

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