

ROBOSAT: Towards an Integrated Robotic Platform for Large-scale Multimodal Wilderness Navigation

Miguel Matey-Sanz^{1,*}, Yuyan Wu¹, Yelyzaveta Pervysheva², Muhammad Safi²,
Andrei Cramariuc³, Irina Mocanu⁴, Oana Cramariuc⁴, Jari Nurmi², Elena Simona Lohan²,
Jose Manuel Claver¹, Esther Dura¹ and Joaquín Torres-Sospedra^{1,5}

¹Universitat de València, Escola Tècnica Superior d'Enginyeria, 46100 Burjassot, Spain

²Tampere Wireless Communication Center, Tampere University, 33720 Tampere, Finland

³Robotic Systems Lab (RSL), ETH Zürich, Zürich, Switzerland

⁴IT Center for Science and Technology (CITST), Romania

⁵valgrAI - Valencian Graduate School and Research Network of Artificial Intelligence, 46022 València, Spain

Abstract

Autonomous robot navigation in the wild has shown great potential in several areas such as rescue, agriculture, military, and planetary exploration. Compared to drones, legged robots are able to carry greater payloads and can flexibly handle dynamic and complex environments. However, the effectiveness of these robots relies on accurate positioning. In wild and unstructured environments, satellite navigation remains challenging due to signal attenuation, multipath propagation, and rapidly changing environmental conditions. Despite existing publicly available datasets for robot navigation in the wild, these datasets generally lack observational data that can be used for reproduction, such as I/Q signals or unfiltered raw navigation data, limiting their value for further improvements in positioning and trajectory algorithms. To address this limitation, the ROBOSAT project aims to establish a framework for collecting large-scale, multi-sensor, high-quality geospatial data across multiple natural regions while improving localization performance by integrating contextual geospatial information. This paper describes the hardware infrastructure for data collection and a proposed methodology for a GIS-based GNSS-enhanced positioning system. Since the project is currently in early stages, the presented results are still preliminary.

Keywords

Global Navigation Satellite Systems (GNSS), Geographic Information Systems (GIS), Robot navigation, GIS-GNSS integration

1. Introduction

The rapid development of autonomous robotic systems, artificial intelligence (AI), and geospatial technologies is transforming the way natural and built environments are perceived, mapped, and monitored. High-resolution three-dimensional Geographic Information Systems (GIS), enriched with multimodal sensor information, are becoming a fundamental component of applications ranging from environmental monitoring and precision forestry to autonomous navigation, infrastructure inspection, and search-and-rescue operations [1, 2]. As autonomous systems increasingly operate in complex outdoor environments, the demand for accurate, large-scale, and continuously updated geospatial information continues to grow.

WIPHAL'26: Work-in-Progress in Hardware and Software for Location Computation October 6–8, 2026, Rome, Italy

*Corresponding author.

✉ miguel.matey@uv.es (M. Matey-Sanz); name.surname@uv.es (Y. Wu); name.surname@tuni.fi (Y. Pervysheva); name.surname@tuni.fi (M. Safi); name.surname@tuni.fi (A. Cramariuc); irina.mocanu@citst.ro (I. Mocanu); name.surname@citst.ro (O. Cramariuc); name.surname@tuni.fi (J. Nurmi); name.surname@tuni.fi (E. S. Lohan); Jose.Claver@uv.es (J. M. Claver); esther.dura@uv.es (E. Dura); Joaquin.Torres@uv.es (J. Torres-Sospedra)

🆔 0000-0002-1189-5079 (M. Matey-Sanz); 0000-0002-1078-3120 (Y. Wu); 0009-0009-7676-0851 (Y. Pervysheva); 0009-0009-4719-2226 (M. Safi); 0000-0002-9301-0253 (A. Cramariuc); 0000-0001-5176-9344 (I. Mocanu); 0000-0002-7499-5704 (O. Cramariuc); 0000-0003-2169-4606 (J. Nurmi); 0000-0003-1718-6924 (E. S. Lohan); 0000-0002-9617-3453 (J. M. Claver); 0000-0002-2603-5549 (E. Dura); 0000-0003-4338-4334 (J. Torres-Sospedra)



© 2026 Copyright for this paper by its authors. Use permitted under Creative Commons License Attribution 4.0 International (CC BY 4.0).

The creation of such multidimensional geospatial representations, however, remains a challenging task. Existing geospatial datasets are often incomplete, lack temporal updates, or provide insufficient detail for robotic perception and navigation in unstructured environments such as forests, mountainous regions, or other natural landscapes [3]. While robots offer an attractive solution for systematic and repeatable data acquisition, autonomous operation under these conditions requires robust locomotion, reliable perception, and the synchronized integration of heterogeneous sensing modalities, including cameras, LiDARs, inertial measurement units (IMUs), and Global Navigation Satellite Systems (GNSS) receivers [4, 5, 6]. The resulting sensing platforms generate large volumes of data whose efficient storage, synchronization, annotation and retrieval constitute significant challenges on their own [7, 8].

An important opportunity arises from the synergy between geospatial information and satellite navigation, where GNSS localization directly produces geospatial data that can subsequently be leveraged to enhance future positioning performance. GNSS remains the primary source of global positioning for outdoor robotic systems, yet its performance can deteriorate significantly due to multipath propagation, non-line-of-sight (NLOS) reception, signal blockage, or intentional interference such as jamming or spoofing [9, 10, 11]. Recent research has shown that contextual information derived from three-dimensional maps and terrain models can improve localization performance by constraining the navigation solution and identifying unreliable satellite observations [12, 13]. Conversely, accurate GNSS positioning is essential for producing precisely georeferenced datasets that serve as the foundation for high-quality GIS products. Nevertheless, scalable frameworks capable of integrating multimodal robotic observations with existing geospatial information remain limited, particularly in unconstrained outdoor environments (e.g., forests, mountains, hilly terrains with unpaved paths) [4, 14].

To address these challenges, the ROBOSAT project investigates an integrated framework that combines autonomous robotic data acquisition, AI-based management of multimodal geospatial information, and GIS-assisted GNSS localization. The project aims to establish a scalable methodology for collecting synchronized GIS and GNSS data in challenging outdoor environments while improving the robustness and accuracy of satellite-based positioning through the exploitation of contextual geospatial information. In addition, ROBOSAT seeks to produce open-access datasets and software tools that support future research in robotics navigation, GIS, and satellite navigation.

This paper presents an overview of the ROBOSAT project objectives (Section 2), the developed robotic measurement platform and the proposed methodology for integrating multiple GIS and GNSS information (Section 3), the experimental environments available within the consortium (Section 4), and discusses the preliminary results from the first data collection campaigns (Section 5).

2. ROBOSAT Project

ROBOSAT¹ is a collaborative research project funded under the EU CHIST-ERA programme, bringing together complementary expertise in robotics, satellite navigation, AI, and GIS from the consortium members: Tampere University (Finland), ETH Zurich (Switzerland), University of Valencia (Spain) and CITST (Romania). The project aims to advance the acquisition, management, and exploitation of multimodal geospatial data in unstructured outdoor environments through the integration of robotics, GIS, AI, and GNSS. The project addresses the challenge of establishing a scalable framework for collecting high-quality geospatial data in natural environments while simultaneously improving localization performance through the integration of contextual geospatial information.

The vision of the project is based on the observation that the relationship between geospatial data and positioning is inherently bidirectional. On the one hand, accurate localization is essential to produce high-quality georeferenced datasets. On the other hand, rich geospatial information can provide environmental context that improves localization accuracy and robustness, particularly under adverse conditions where GNSS measurements are degraded by multipath, NLOS propagation, jamming, or spoofing. ROBOSAT therefore investigates a framework in which improved positioning enhances the

¹<https://www.robosat.eu/index.html>

quality of collected datasets, while progressively richer datasets contribute to more robust localization algorithms. To realize this vision, the project is structured around three complementary research pillars:

- **Scalable multimodal data acquisition through autonomous robotic platforms.** ROBOSAT employs a quadrupedal robot capable of operating in challenging outdoor environments such as forests, mountainous regions, and other unstructured terrains. The robotic platform is equipped with a multimodal sensing payload (see Section 3.1), enabling repeatable acquisition campaigns while providing accurately synchronized measurements suitable for geospatial mapping.
- **Management of large-scale multimodal geospatial datasets.** The diversity of sensing modalities generates heterogeneous data with different spatial and temporal characteristics, requiring dedicated mechanisms for storage, indexing and retrieval. ROBOSAT investigates AI-based approaches for the automatic labelling of collected data, semantic organization, and natural-language-based querying of the resulting database.
- **Integration of multimodal GIS data into GNSS localization algorithms.** Existing GNSS solutions can suffer significant performance degradation in complex environments due to signal blockage, multipath propagation, and intentional or unintentional interference. ROBOSAT investigates how contextual information extracted from multimodal GIS data can support more accurate and robust positioning. More concretely, ROBOSAT proposes the integration of 3D GIS data (e.g., building footprint models, terrain elevation, or urban structure maps) in several of the GNSS receiver stages (see Figure 1): particularly in the pre-correlation and post-correlation stages, which have gathered few attention in the literature, but also in the navigation stage, which has been the main focus of GIS-GNSS integration.

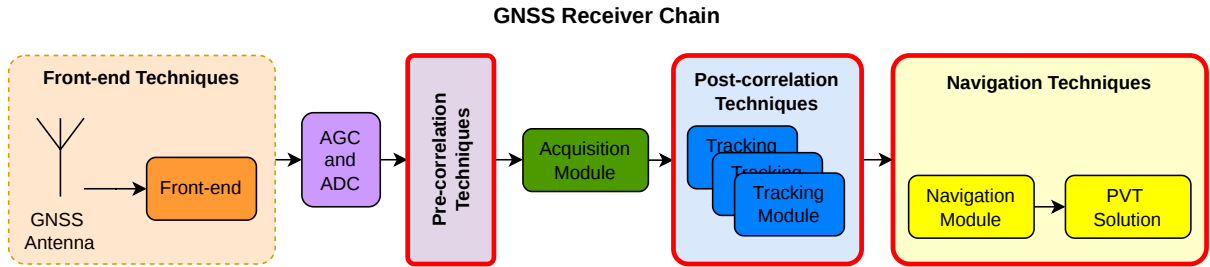


Figure 1: Block diagram illustrating GNSS receiver stages, with red blocks emphasizing the possible integration places of GIS information that have been less studied in the literature so far compared to the navigation-domain integration.

Overall, ROBOSAT aims to establish an integrated ecosystem for robotic geospatial data collection that combines autonomous sensing, intelligent data management, and context-aware localization. Beyond the scientific developments in robotics and navigation, the project will deliver open multimodal datasets supporting future research in robotics, environmental monitoring and autonomous navigation.

As the project is currently in early stages, this paper does not aim to provide a complete evaluation of the proposed framework. Instead, it presents the overall vision of ROBOSAT, introduces the experimental infrastructure that has been established across the consortium, and reports the first preliminary results obtained from the initial data collection campaigns. These results constitute the foundation for the more comprehensive validation activities that will be carried out during the remainder of the project.

3. Materials & Methods

3.1. Robotic Platform

To meet the data collection requirements of unstructured environments in the wild, we developed a scalable multidimensional satellite-based 3D GIS data collection platform to be integrated on the

ANYmal quadrupedal robot, which can autonomously perform long-distance missions in challenging terrain. Developed by ANYbotics, a spin-off from ETH Zurich, ANYmal provides excellent adaptability to rugged environments and climbing capability. To improve its long-term autonomous performance, several hardware and software upgrades have been introduced. The original series elastic actuators were replaced with direct-drive motors, increasing the robot's maximum joint torque, and thus its effective payload and operation range. Based on the system identification method in [15], a preliminary dynamic model has been established, laying the foundation for the sim-to-real transfer of reinforcement learning control strategies. The upgraded platform has been successfully validated through experiments on standing posture stabilization, high-frequency joint motions, state estimation, and blind locomotion policy training.

The robot is equipped with a sensor suite that enables a consistent and repeatable collection of local data for integration with GIS. The suite was designed based on a comprehensive evaluation of sensing technologies [16] supporting navigation, perception, and signal acquisition. Two LiDARs are used for 3D reconstruction of the surrounding environment. Multiple HDR cameras capture visual information for semantic understanding and compatibility with standard vision-based AI pipelines. A range of IMUs with different performance levels and price points were incorporated and evaluated to support accurate high-frequency motion estimation. A Leica Total Station tracks a prism mounted on top of the robot, providing sub-millimeter range precision and millimeter-level accuracy for ground-truth trajectories. The current platform employs a standard Real-Time Kinematic (RTK) GNSS receiver for GNSS signal acquisition. A visualization of the sensor suite is shown in Figure 2.

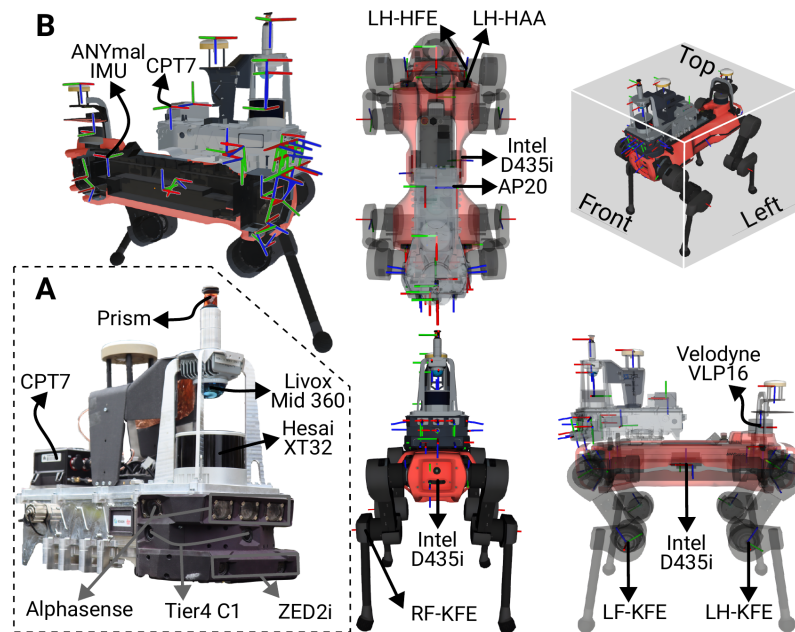


Figure 2: Sensor placement visualization of the entire sensor suite. A) Shows the spatial relationships of the sensors on the ANYmal payload, and B) shows the sensors of the ANYmal base platform components. Each colored axis represents a sensor or joint frame. For brevity, repeated sensors are not shown (e.g., $6 \times$ Intel RealSense D435i depth cameras).

To extend the capabilities of the standard RTK-GNSS receiver, an enhanced GNSS subsystem based on an In-phase/Quadrature (I/Q) data grabber is currently under development and testing. This device supports diagnostics, debugging, and receiver algorithm development by providing access to raw I/Q data, the most information-rich representation of the wireless channel. The complex recorded samples enable improvements to positioning algorithms at different receiver stages and facilitate detailed characterization of interference, including spoofing and jamming. In addition, recorded datasets can be replayed for reproducible experiments and offline analysis, allowing receiver architectures and signal-processing algorithms to be evaluated under identical signal conditions. The I/Q data grabber

is based on the MGSE[®]-REC I/Q acquisition unit, licensed to Tampere University. Its single-channel version includes three FPGA configurations covering the L1/E1 frequency bands. This enables the device to acquire signals from the GNSS in these L1/E1 bands.

The radio frequency (RF) front-end supports external clock synchronization (10 MHz reference) and hardware trigger interfaces to ensure time-aligned acquisition of RF signals with other onboard sensors. The antenna used in conjunction with the MGSE[®]-REC-SC is the navXperience 3G+C mobile. The 3G+C mobile supports reception of signals from four major satellite navigation systems, GPS, Galileo, GLONASS, and BeiDou, as well as L-band correction data services, operating across two frequency bands: 1150–1300 MHz and 1525–1610 MHz.

3.2. Data Infrastructure

To support secure data ingestion, sharing, and long-term preservation, a two-tier storage infrastructure has been established at the University of Valencia and the Tirant node of the Spanish Supercomputing Network. A local Network Attached Storage (NAS) system based on a Synology DiskStation DS1525+ has been deployed, as shown in Fig. 3. The system contains five Seagate Ironwolf 12 TB (ST12000VN0008) configured in RAID-5 with a hot spare disk, providing approximately 48 TB of storage. In addition, the system has two Synology 400 GB (SNV3410-400G) SSDs for a read and write cache. The NAS runs Synology DiskStation Manager (DSM) to manage the stored data, providing hardware encryption and firewall mechanisms. This local infrastructure is complemented by a tape backup system at the Tirant supercomputing node, providing geographic redundancy and long-term data preservation.

The system can store any kind of structured or unstructured data. Currently, the stored datasets include raw images, 3D point clouds, IMU measurements, GNSS logs, and raw I/Q binary captures generated by consortium measurement campaigns.



Figure 3: The NAS system devoted to ROBOSAT project.

3.3. GNSS-GIS Integration Architecture

The integration of GNSS signal processing with 3D GIS data has become an emerging research direction for improving robot navigation in environments affected by NLOS reception and multipath propagation. Prior work has shown that aligning ray-traced path predictions with correlator-level signal samples can significantly reduce positioning errors in dense urban environments [17]. However, embedding GIS-derived environmental information directly into the I/Q-domain processing pipeline has not been systematically explored. Motivated by this, we proposed a GNSS-GIS integration architecture based on raw I/Q data. The proposed architecture enables GIS information to be incorporated at three fundamentally different stages of the GNSS receiver processing chain (see Figure 1): the pre-correlation

stage, where processing operates directly on raw I/Q samples; the post-correlation stage, operating at the tracking loop level, and the navigation stage, where pseudorange and carrier-phase observables have already been generated.

Figure 4 illustrates the proposed GIS integration strategy at different stages of the GNSS receiver processing chain. At the pre-correlation stage, GIS contextual data such as 3D environment geometry can be combined with multi-antenna arrays for spatial filtering by adjusting amplitude/phase weight across I/Q streams. GIS data can also be useful to identify regions subject to multipath, reflections, or localized interferences and used to dynamically filter and suppress interferences within the raw I/Q data. Moving to the post-correlation stage, three-dimensional spatial datasets are used to provide environmental context for signal acquisition. By applying geometric ray tracing to predict which satellites are likely to have an unobstructed line-of-sight (LOS) to the receiver at a given location, a sky visibility mask can be constructed to constrain the two-dimensional correlator search space across both code-delay and Doppler-shift dimensions. As a result, unnecessary computations for satellites predicted to be blocked can be avoided, while detection thresholds and coherent integration times can be adapted on a per-satellite basis according to the expected received signal power, improving both computational efficiency and acquisition robustness. Finally, in the navigation stage, three-dimensional building models provide environmental information for validating GNSS pseudorange measurements after signal tracking. Predicted LOS propagation paths are used to assess the consistency of pseudorange residuals and identify measurements that are likely affected by NLOS propagation. These observations can later be excluded from the navigation filter or assigned lower weights during position estimation [18].

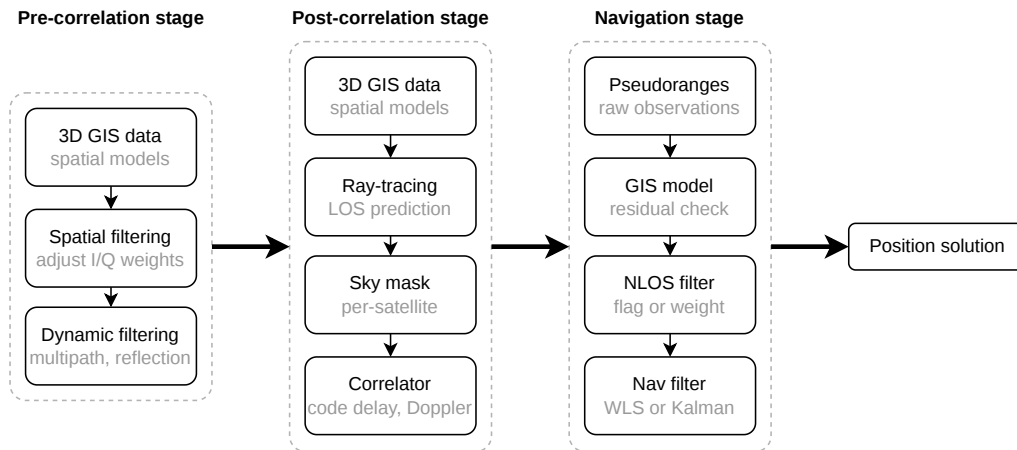


Figure 4: Block diagram illustrating GIS integration ideas at different GNSS receiver stages.

Regarding the real-world applicability of the proposed method, the required GIS contextual data (e.g., topographic data, digital elevation models, 3D buildings, etc.) is increasingly available through open-access national and regional GIS databases such as those provided by Copernicus² (EU), National Land Survey of Finland³, swisstopo⁴ (Switzerland) or Instituto Geográfico Nacional⁵ (Spain). Furthermore, for unmapped natural environments, local 3D representations can be generated dynamically on board the platform using the robot's perception suite (e.g., 3D LiDARs), ensuring the feasibility of GIS-GNSS integration even when prior map coverage is sparse.

²<https://dataspace.copernicus.eu/data-collections>

³<https://maanmittauslaitos.fi/en>

⁴<https://www.swisstopo.admin.ch/en/>

⁵<https://www.ign.es>

4. Experimental Setup

The experimental setups established across the ROBOSAT consortium support both laboratory and field data collection for the acquisition of synchronized multimodal datasets.

At Tampere University, static measurements have preliminarily been performed using the MGSE[®]-REC-SC front-end in a controlled rooftop environment. A permanently installed NovAtel rooftop antenna provides a stable open-sky view for reference signal collection, while a navXperience 3G+C mobile antenna is additionally employed to enable antenna performance comparison. Highly accurate ground-truth positions are obtained through Precise Point Positioning (PPP)-RTK processing. For dynamic data collection, the MGSE[®]-REC-SC operates as a portable unit powered via a USB connection to a laptop, using the navXperience 3G+C mobile antenna for all field measurements. Dynamic measurements are to be further conducted in four representative scenarios relevant to GNSS performance characterization: (i) open-sky conditions in an unstructured outdoor area, serving as the benchmark for all subsequent experiments; (ii) forested hiking trails in the Tampere region to investigate signal degradation caused by natural obstructions; (iii) the Tampere city center to evaluate urban multipath effects; and (iv) mixed indoor-outdoor environments on the Tampere University campus. All measurement campaigns are to be systematically annotated according to environmental conditions and transition events, which allows for a direct correlation between propagation environments and the recorded I/Q data. Several approaches for obtaining accurate ground-truth trajectories during dynamic measurements are currently under investigation.

At ETH Zurich, data collection so far comprises 49 autonomous robot missions [19], totaling more than 10 km of traversal and over five hours of recorded multimodal data using the customized ANYmal platform. All onboard sensors are hardware-synchronized, providing tightly aligned measurements together with millimeter-level ground-truth trajectories obtained from a Leica MS60 Total Station. The resulting datasets provide a valuable benchmark for robotic localization, GNSS positioning, and GNSS signal-processing algorithm evaluation. At the moment, the data is publicly available only through a registration and login process. New measurements are envisaged, which will be added on the ROBOSAT server with more open access at a later date.

At the University of Valencia, the laboratory is equipped with a heterogeneous set of positioning technologies, including Wi-Fi received signal strength indicator (RSSI) fingerprinting, Wi-Fi Fine Time Measurement (FTM) for round-trip time estimation, antenna arrays for Bluetooth Low Energy (BLE) angle of arrival (AoA) measurements, and Ultra-Wideband (UWB) equipment supporting both time of arrival (ToA) and angle of arrival (AoA) estimation. In addition, the laboratory includes a neuromorphic camera for event-based sensing and an anechoic chamber measuring 5 m $\times$ 8 m $\times$ 5 m, supporting antenna characterization and wireless sensor device testing over the frequency range from 300 MHz to 110 GHz. These facilities provide a controlled environment for RF experimentation and sensor-performance evaluation in multimodal positioning research.

At CITST, we started from the Mimir application [20] – an open-source Android application, developed for research purposes at Tampere University and released under the Apache-2.0 license, designed to log data from the sensors available on smart devices. It supports raw GNSS measurements, positions provided by the GPS provider and navigation messages, as well as readings from the accelerometer, gyroscope, magnetometer, barometer, step counter, and step detector. Sampling rates can be configured individually for each sensor, although the available measurements and the effective rates ultimately depend on the hardware capabilities and on the scheduling behaviour of the operating system.

The version developed in this work logs each session in CSV format. Each row includes the measurement type, timestamps, sensor values, accuracy information, and relevant metadata, providing a structured format suitable for filtering, analysis, visualization, and machine-learning workflows. In addition, an image is acquired and saved in synchronization with the logged sensor data measurements.

Future data collection campaigns will be conducted in Romania in order to acquire synchronized positioning data and images in natural, non-urban environments. The Mimir application will be operated by several users, following an acquisition protocol similar to the one used with the ANYmal robot. Unstructured terrain containing vegetation, rocks, snow, and other natural obstacles will be explored.

The resulting datasets will include synchronized raw GNSS measurements, position estimates, inertial and barometric data, together with the corresponding images, complementing existing robotic datasets with measurements collected in environments that are difficult to reproduce under controlled laboratory conditions.

5. Preliminary Results

Current work focuses on developing autonomous robotic systems and exploiting multimodal observations to support next-generation positioning and navigation algorithms. Preliminary results have been obtained in two complementary directions: (i) evaluation of GNSS positioning performance using the ANYmal robotic platform and (ii) integration of robotic observations with external geospatial information.

Multiple trajectories collected using the customized ANYmal platform under realistic outdoor conditions were analysed to evaluate the GNSS positioning performance. Three positioning solutions were considered: the standalone real-time navigation solution (RT), the tightly coupled GNSS-INS solution (TC), and a post-processed solution (POS) generated from RINEX observations using RTKLIB. Ground-truth trajectories were obtained using a Leica MS60 Total Station tracking a prism mounted on the robot. All trajectories were temporally synchronized and transformed into a common local East-North-Up (ENU) reference frame to enable direct comparison. Figure 5 presents representative trajectory comparisons in the local ENU frame in an industrial environment (Figure 5(a)) and a forested environment (Figure 5(b)). In the case of the industrial environment, the platform suffered a malfunction during the data collection causing missing POS and GT trajectories (upper-left loop). Both the TC and POS solutions closely follow the ground-truth trajectory, whereas the real-time solution exhibits larger deviations in segments affected by environmental conditions and terrain variation. However, the POS solution is noisier and less stable than the other solutions at certain locations in the trajectory. To further interpret positioning performance, the recorded trajectories were analysed together with airborne LiDAR datasets and satellite skyplots derived from the GNSS observations. High-resolution digital elevation models and classified surface representations provide an environmental context for identifying terrain, vegetation, and built structures, while the corresponding skyplots describe satellite visibility during the experiments. These datasets support the analysis of positioning behaviour with respect to signal obstruction, multipath propagation, and satellite geometry.

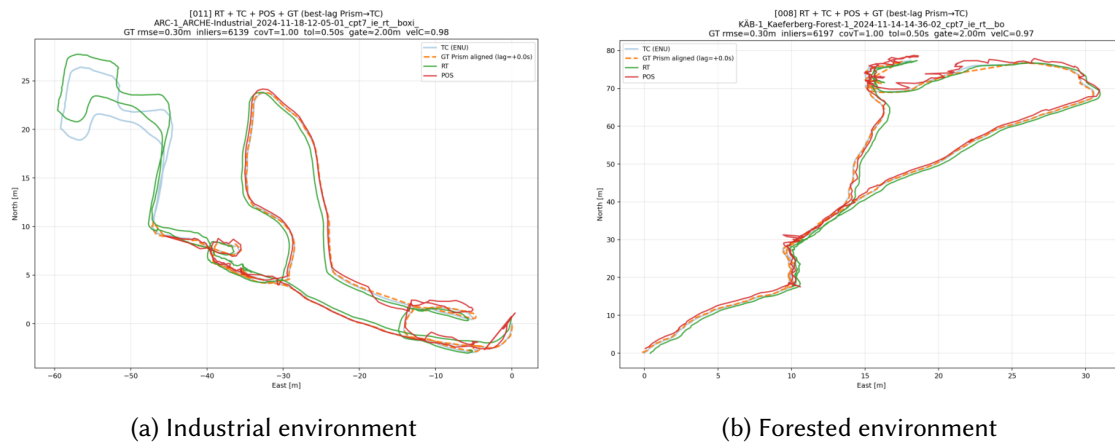
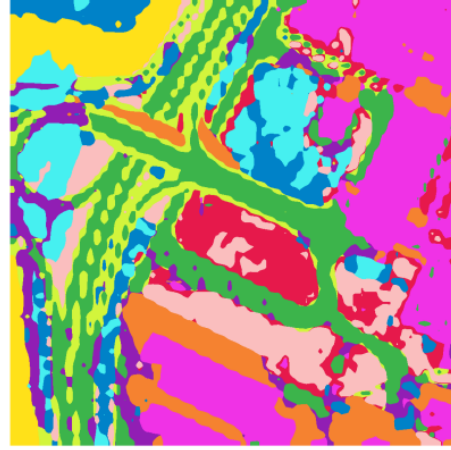


Figure 5: Comparison of real-time (RT), tightly coupled (TC), post-processed (POS), and ground truth (GT) trajectories in the local ENU frame for an (a) industrial test environment and (b) forested environment.

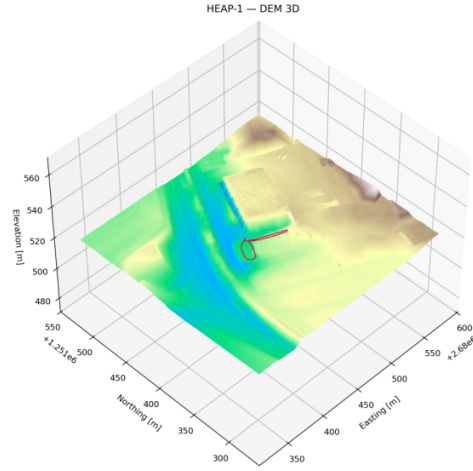
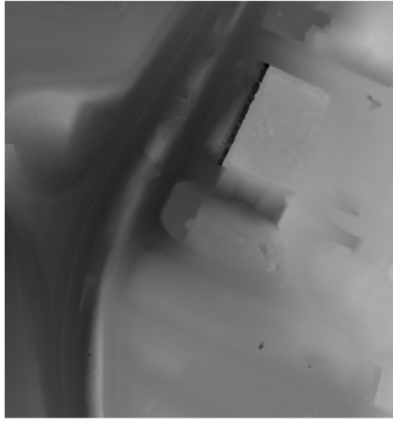
Beyond positioning evaluation, geospatial information from other sources can be further integrated and leveraged. For example, Figure 6 shows how satellite data taken around the same time can be overlain with the robot trajectory to obtain more comprehensive information about the environment. In the future, we plan to leverage this data further to, for example, perform better global path planning,



(a) RGB satellite image.



(b) DINOv3 features with K-means= 10.



(c) Elevation map of the environment, both in 2D and 3D from swissALTI3D. The right side also shows the overlay of the robot path in the environment.

Figure 6: Figures showing how satellite data from the Swiss Federal Office of Topography can be combined with the robot dataset to obtain more contextual and semantic information about the environment.

where from experience, we can predict how costly traversing different terrains is. This would enable more ubiquitous robotics applications, as robots would now be able to traverse more rough terrains, and navigate more challenging environments such as forests and mountains.

6. Ongoing and Future Work

The next stages of the project will focus first on developing a secure storage infrastructure capable of handling approximately 25–300 TB of multimodal robot and GNSS/I/Q data, incorporating standardized formats, automatic indexing based on parameters such as GNSS information, timestamps, and data types, as well as efficient query and download capabilities. Building on this infrastructure, AI-assisted data annotation methods will be implemented to classify environments and robot motion, while also performing automated quality-control procedures to assess aspects such as sensor synchronization, data completeness, and image quality to ensure a reliable and searchable dataset.

Then, machine learning (ML) and other statistical methods will be applied to identify patterns and correlations across the different modalities. These analyses will support terrain characterization, robot performance analysis, and accessibility assessment. In parallel, additional I/Q data will be collected under a wider range of scenarios, including open-sky and multipath conditions. In particular, data collected during Jammertest 2026 [21] under different interference conditions will be used to investigate

the integration of GIS information at different stages of GNSS processing and to explore how map data can contribute to improved navigation and resilience against interference.

Finally, ML-based methods will be investigated to establish relationships between environmental context and the quality of received GNSS signals. In this approach, images will first be segmented to identify relevant environmental components, which will subsequently be correlated with signal-quality indicators extracted from the raw GNSS observations. This analysis is expected to provide further insight into how environmental characteristics affect GNSS signal quality and to contribute to more robust navigation in challenging environments.

7. Conclusions

In this work, we introduced ROBOSAT, a scalable MultiGIS data collection platform designed to support robot navigation research in unstructured environments. The platform enables the integration of GNSS observations with high-resolution GIS data for environmentally aware robot navigation. Preliminary results demonstrate the potential of environmental context to enhance positioning reliability. This work establishes a solid technical foundation for a unified GIS-GNSS processing architecture. Future work will focus on collecting additional multimodal datasets across diverse wilderness scenarios to further validate and extend the proposed framework while establishing an efficient multimodal data management system.

Acknowledgements

This research is financially supported by the Research Council of Finland under the ROBOSAT project under ERA-NET CHISTERA call, with grant number 368663; by MICIU/AEI/10.13039/501100011033 and the EU, with grant number PCI2025-163241, and by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI – UEFISCDI, project number 84/2025 ERANET-CHISTERA-IV-ROBOSAT, within PNCDI IV.

Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT to correct grammar and spelling. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

References

- [1] P. La Hera, O. Mendoza-Trejo, O. Lindroos, H. Lideskog, T. Lindbäck, S. Latif, S. Li, M. Karlberg, Exploring the feasibility of autonomous forestry operations: Results from the first experimental unmanned machine, *Journal of Field Robotics* 41 (2024) 942–965. doi:10.1002/rob.22300.
- [2] J. Filipe Ferreira, D. Portugal, P. Peixoto, Current landscape on artificial perception for outdoor robotics for a sustainable environment, in: *Recent Advances in Robotic Perception for Forestry*, Springer, 2026, pp. 3–39. doi:10.1007/978-3-032-15812-3_1.
- [3] V. Navarro, S. del Rio, M. del Mar Millán, A. Messina, J. Ventura-Traveset, GSSC Now: ESA thematic exploitation platform for navigation digital transformation. enhancing GNSS scientific research, *Advances in Space Research* 74 (2024) 2728–2751. doi:10.1016/j.asr.2024.02.016.
- [4] M. P. Cristóvão, D. Portugal, Lost in the woods? a survey of localization strategies for forest robotics, *Recent Advances in Robotic Perception for Forestry* (2026) 347–373. doi:10.1007/978-3-032-15812-3_13.

- [5] D. Kim, D. Carballo, J. Di Carlo, B. Katz, G. Bledt, B. Lim, S. Kim, Vision aided dynamic exploration of unstructured terrain with a small-scale quadruped robot, in: 2020 IEEE Int. Conf. on Robotics and Automation (ICRA), IEEE, 2020, pp. 2464–2470. doi:10.1109/ICRA40945.2020.9196777.
- [6] R. Grandia, F. Jenelten, S. Yang, F. Farshidian, M. Hutter, Perceptive locomotion through nonlinear model-predictive control, IEEE Transactions on Robotics 39 (2023) 3402–3421. doi:10.1109/TRO.2023.3275384.
- [7] J. Wang, R. Wang, Z. Bo, H. Li, C. Wang, Y. Fang, Multidimensional visualization analysis based on large-scale GNSS data, Open Astronomy 33 (2024) 20220037. doi:10.1515/astro-2022-0037.
- [8] I. E. Mehr, A. Minetto, F. Dovis, E. Pica, C. Cesaroni, V. Romano, An open architecture for signal monitoring and recording based on SDR and docker containers: A GNSS use case, in: IEEE EUROCON 2023-20th International Conference on Smart Technologies, IEEE, 2023, pp. 66–71. doi:10.1109/EUROCON56442.2023.10199078.
- [9] P. Xu, G. Zhang, B. Yang, L.-T. Hsu, Machine learning in GNSS multipath/NLOS mitigation: Review and benchmark, IEEE Aerospace and Electronic Systems Magazine 39 (2024) 26–44. doi:10.1109/MAES.2024.3395182.
- [10] D. Hai, C. L. Tsang, G. Zhang, Analysis of GNSS multipath effects and performance degradation in vegetated environments, IEEE Transactions on Instrumentation and Measurement (2026). doi:10.1109/TIM.2026.3709404.
- [11] R. Morales-Ferre, P. Richter, E. Falletti, A. De La Fuente, E. S. Lohan, A survey on coping with intentional interference in satellite navigation for manned and unmanned aircraft, IEEE Communications Surveys & Tutorials 22 (2019) 249–291. doi:10.1109/COMST.2019.2949178.
- [12] M. Adjrard, P. D. Groves, Enhancing least squares GNSS positioning with 3D mapping without accurate prior knowledge, Navigation: Journal of The Institute of Navigation 64 (2017) 75–91. doi:10.1002/navi.178.
- [13] Y.-H. Lu, J.-Y. Han, Gns satellite visibility analysis based on 3D spatial information in urban areas, The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences 43 (2020) 123–128. doi:10.5194/isprs-archives-XLIII-B4-2020-123-2020.
- [14] J. F. Ferreira, D. Portugal, M. E. Andrada, P. Machado, R. P. Rocha, P. Peixoto, Sensing and artificial perception for robots in precision forestry: A survey, Robotics 12 (2023) 139. doi:10.3390/robotics12050139.
- [15] F. Bjelonic, F. Tischhauser, M. Hutter, Towards bridging the gap: Systematic sim-to-real transfer for diverse legged robots, arXiv preprint arXiv:2509.06342 (2025).
- [16] J. Frey, T. Tuna, L. F. T. Fu, C. Weibel, K. Patterson, B. Krummenacher, M. Müller, J. Nubert, M. Fallon, C. Cadena, et al., Boxi: Design decisions in the context of algorithmic performance for robotics, Robotics: Science and Systems (RSS) (2025). doi:10.3929/ethz-b-000732769.
- [17] R. Kumar, M. G. Petovello, 3d building model-assisted snapshot positioning algorithm, GPS Solutions 22 (2018) 12. doi:10.1007/s10291-017-0661-2.
- [18] L.-T. Hsu, Y. Gu, S. Kamijo, NLOS correction/exclusion for GNSS measurement using RAIM and city building models, Sensors 15 (2015) 17329–17349. doi:10.3390/s150717329.
- [19] J. Frey, T. Tuna, F. Fu, K. Patterson, T. Xu, M. Fallon, C. Cadena, M. Hutter, Grandtour: A legged robotics dataset in the wild for multi-modal perception and state estimation, arXiv preprint arXiv:2602.18164 (2026). doi:10.48550/arXiv.2602.18164.
- [20] A. Grenier, E. S. Lohan, A. Ometov, J. Nurmi, Towards smarter positioning through analyzing raw gnss and multi-sensor data from android devices: A dataset and an open-source application, Electronics 12 (2023). doi:10.3390/electronics12234781.
- [21] Jammertest, Jammertest 2026, 2026. URL: <https://www.jammertest.no/jammertest-2026/>.