Towards Multimodal Autonomous Exploration Onboard Legged Robot

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Abstract

Autonomous exploration brings various challenges for quadrupedal robots, including state estimation, route planning, stable locomotion, battery management, and limited computing power. The project fills a research gap in current research by developing a fully integrated system for autonomous quadrupedal robot exploration of an unknown environment. We demonstrate the holistic development in both simulation and real-world experiments, showing real-time performance in a room-sized testing scenario for exploration, deploying a Unitree Go2 quadrupedal robot equipped with a NVIDIA Jetson Orin and a Livox Mid360 LiDAR.

Background

- RESPLE is a novel recursive Bayesian estimation framework using B-splines for continuous-time 6-DoF dynamic motion estimation. RESPLE is the first estimation framework that manages to use B-spline recursive estimation in continuous time. The authors of RESPLE prove in simulated and real-world evaluations that RESPLE outperforms other state-of-the-art frameworks in accuracy and robustness while having real-time efficiency.
- TARE-Planner introduces a hierarchical exploration framework maintaining a high and low level resolution representation of the environment. The exploration path is computed coarsely at the global scale and finely in the local scale and merged together into one complete exploration path, achieving efficiency and scalability for large environments.
- There are existing Simulation Environments, open-source autonomy stacks provide simulations and environments for robots. However, these frameworks lack key components of the proposed system: they do not integrate RESPLE, do not support deployment of the TARE-Planner, or do not include validation on a real quadrupedal robot.

Contributions

The contribution of this project is to:

- Demonstrate the holistic development in both simulation and real-world experiments, showing real-time performance in a room-sized testing scenario for exploration.
- For testing and validation purposes, multiple simulation environments in RViz and Gazebo were developed or adapted from existing simulations. Real-world experiments conducted using a Unitree Go2 quadrupedal robot equipped with a Livox Mid360 LiDAR with an integrated IMU and an NVIDIA Jetson Orin for onboard computation.
- Comparison of performance of RESPLE against another LiDAR-Inertial state estimation in simulation.

System Design

Both RESPLE and TARE-Planner are developed in ROS 2 Humble. This made it possible to integrate both modules with little changes. Each module operates as a separate ROS2 node using a publish-subscribe architecture to communicate asynchronously between the components. In Figure 1, an overview of the data flow within the integrated system is shown. Detailing how captured sensor data is used by RESPLE for state estimation, which is used by TARE-Planner to generate exploration paths and corresponding locomotion commands.

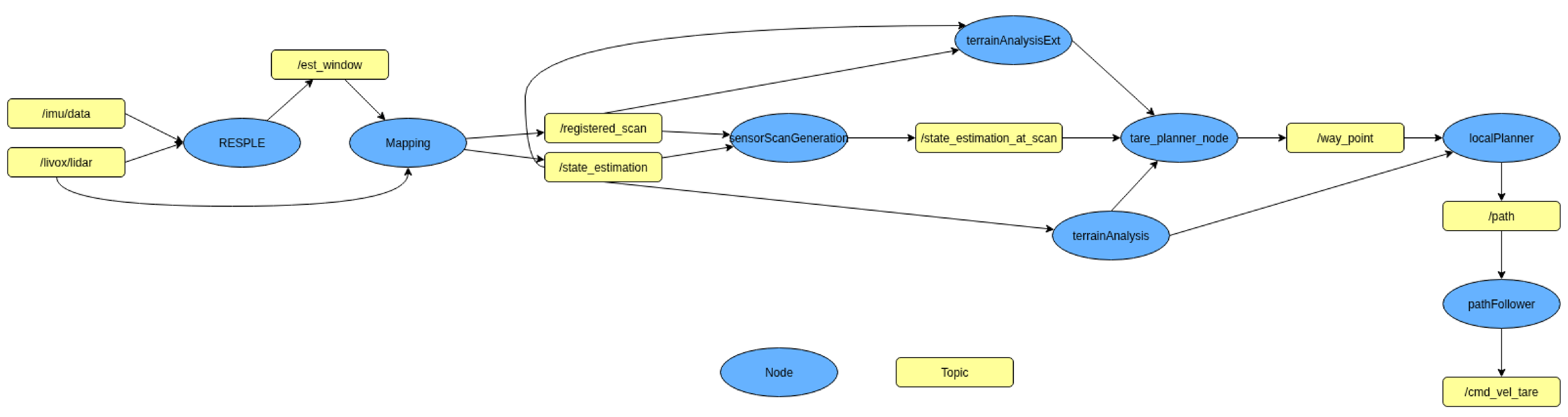

Figure 1: Overview of the data flow within the complete integrated system, showing connections of ROS2 nodes and topics.

Evaluation & Conclusion

To evaluate the influence of introducing RESPLE as the LIO framework within the system pipeline is a simulated Go2 robot was equipped with a simulated Mid360 for LiDAR and IMU sensor data, and was deployed in a simulated maze environment depicted in Figure 2. Each run terminated after 20 minutes or if TARE-Planner considered the environment explored.

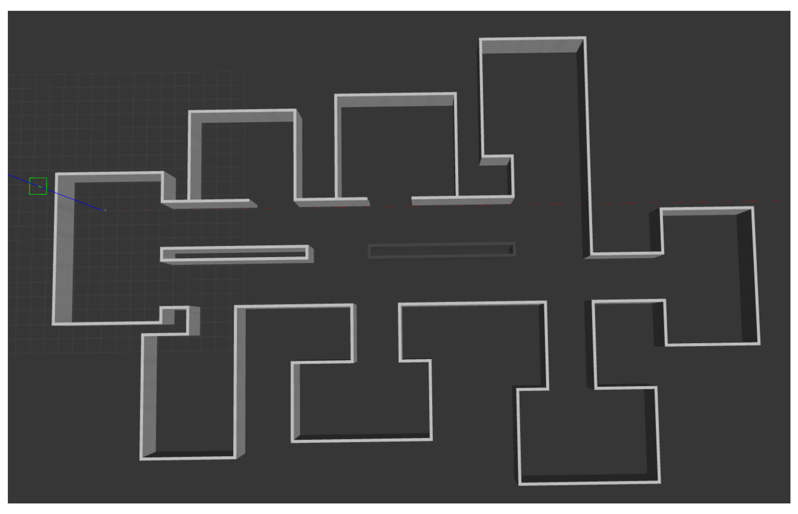

Figure 2: Maze environment as used in the experiment

- RESPLE achieves an average of 2269 m^3 of explored area, compared to 1506.75 m^3 with Point-LIO.
- RESPLE runs result in a more detailed exploration path and remain stable without noticeable drift, whereas Point-LIO suffers from drift across multiple runs (Figures 3 and 4).

These results indicate that RESPLE is a more stable and reliable LIO framework providing better exploration performance under similar experimental conditions, making RESPLE a better fit for the autonomous exploration system on quadrupedal robots.

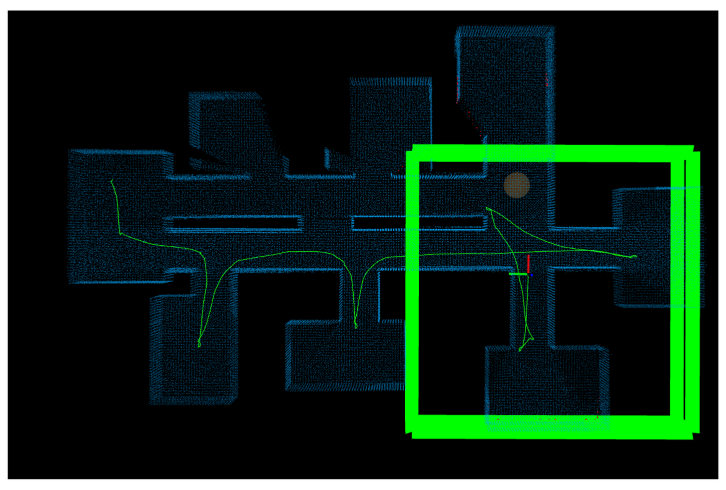

Figure 3: RESPLE run.

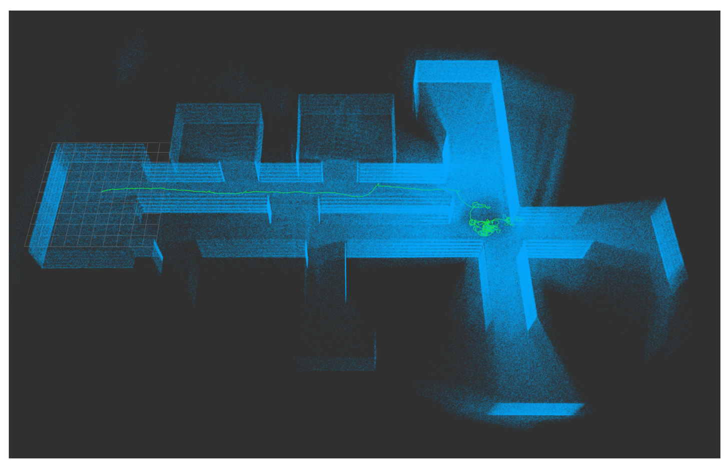

Figure 4: Point-LIO run.

Real-world experiments were conducted with the Unitree Go2 configured as in Figure 5. Even in a limited lab environment, exploration was achieved, where the robot had to navigate around obstacles, scan behind them, and return to the starting point upon completion.

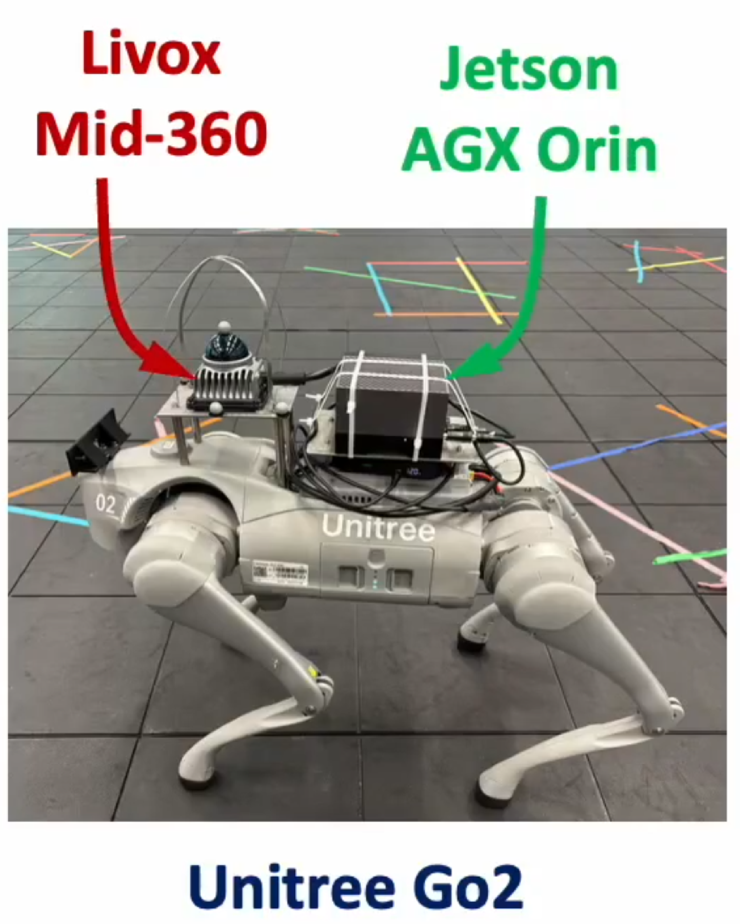

Figure 5: Unitree Go2 setup for lab environment testing.

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