InternPro Weekly Progress Update

Name	Email	Project Name	NDA/ Non-NDA	InternPro Start Date	OPT
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Progress

Include an itemized list of the tasks you completed this week.

#	Action Item/ Explanation	Total Time This Week (hours)
1	Debugging Visual Odometry for Stationary and Dynamic Conditions	3
2	Transitioning to GNSS-IMU Fusion and Validation	3
3	Integrating SLAM and Final System Validation	3
4	Visual-Inertial Odometry (VIO) and Sensor Fusion Techniques	3
5	Simulated Sensor Models and Their Impact on Robot Perception	3
6	SLAM in Structured and Unstructured Outdoor Environments	3
7	Next week plan	1
8	Report writing	1
	Total hours for the week:	20

Verification Documentation:

Action Item 1: Debugging Visual Odometry for Stationary and Dynamic Conditions – 3 hour(s).

Project Work Summary

- Initial observations revealed that the visual odometry (VO) node produced erratic position estimates even when the robot was stationary, with logs showing incremental drift (e.g., x=1.04, y=-1.04, z=1.04). To isolate the issue, I first verified that the /front_camera/image_raw topic was active using ros2 topic hz, confirming image publishing at 30Hz.
- Next, I instrumented the process_image callback with debug logs to track feature extraction and matching. Visualizing ORB keypoints using cv2.drawKeypoints() revealed that ambient lighting variations in the Gazebo world caused false feature matches between consecutive frames.
- To suppress noise, I implemented a dynamic threshold, discarding pose updates unless at least 15 high-confidence matches were found.

- A critical discovery was mismatched camera intrinsics: the hardcoded fx=554.38 in the VO node did not align with Gazebo's simulated camera parameters. By running gz topic -e /gazebo/default/camera/link/camera/image, I extracted the ground-truth intrinsics and updated the K matrix, correcting errors in essential matrix decomposition.
- The scaling logic for translation vectors (t_scaled) was also flawed. Instead of a fixed step_size=0.1, I normalized the t vector using np.linalg.norm(t) and clamped it to a maximum of 0.05 meters per update to prevent artificial motion during static periods.
- Finally, I refined the odometry message's covariance matrix, increasing uncertainty in the Z-axis and yaw orientation to reflect monocular VO's limitations. This adjustment improved downstream fusion in robot_localization, stabilizing the filtered pose output.

Action Item 2: Transitioning to GNSS-IMU Fusion and Validation – 3 hour(s).

Project Work Summary

- With visual odometry stabilized, the next objective was to integrate absolute positioning using simulated GNSS (GPS) and IMU data to address VO's scale ambiguity and drift. Initial tests revealed the custom GNSS node (fake_gps_publisher.py) failed to publish data due to incorrect Gazebo-ROS bridge configuration.
- First, I diagnosed why /gazebo/model_states was not populating. Launching Gazebo with ros2 launch gazebo_ros gazebo.launch.py instead of gzserver alone ensured ROS plugins were loaded. Adding debug logs to the GNSS node's callback revealed the robot's model name mismatch: the code expected husky_robot, but Gazebo reported husky. Correcting this allowed the node to extract the robot's ground truth pose.
- The GNSS simulation initially used naive latitude/longitude scaling (LAT_SCALE = 1e-5), which inaccurately mapped Gazebo's Cartesian coordinates to geographic values. To fix this, I integrated pyproj for proper UTM conversions, defining a local origin at (37.4275°N, -122.1697°W) and projecting Gazebo's (x,y) to UTM (easting, northing), then converting back to geodetic coordinates with realistic noise (±0.0000045° ≈ 0.5m).
- Concurrently, the IMU plugin in the Husky's SDF lacked critical noise parameters, causing [Err] [Sensor.cc:510] warnings. I added Gaussian noise blocks for angular velocity (stddev=0.0003394 rad/s) and linear acceleration (stddev=0.000981 m/s²), aligning with consumer-grade IMU specifications.
- To fuse GNSS and VO, I configured robot_localization's EKF node with two odometry sources: /vo/odometry (VO): Enabled for x, y, z position, disabled for orientation. /odometry/gps (GNSS): Fused as a global pose source with high covariance to account for simulated multipath errors.
- Validation involved teleoperating the robot in Gazebo while monitoring ros2 topic echo /odometry/filtered. The GNSS data corrected VO's relative drift, but sudden jumps occurred due to mismatched frame IDs. By adding a static transform from gps_link to base_link and ensuring all sensors used use_sim_time:=true, the fused output stabilized.

Action Item 3: Integrating SLAM and Final System Validation – 3 hour(s).

Project Work Summary

- With visual odometry (VO) and GNSS-IMU fusion operational, the final phase focused on integrating SLAM (Simultaneous Localization and Mapping) to create a navigable 2D occupancy grid of the Gazebo farmland environment. The goal was to unify perception, localization, and mapping into a cohesive system for autonomous navigation.
- I began by installing the ROS 2 SLAM Toolbox package (sudo apt install ros-humble-slam-toolbox) and retrofitting the Husky robot with a simulated LiDAR sensor. The LiDAR's URDF definition was updated to include realistic noise parameters, reducing <stddev> from 0.1 to 0.05 in the <noise> block to minimize ghost obstacles caused by sensor artifacts in open farmland.
- In the launch file, the async_slam_toolbox_node was configured with use_sim_time:=true to synchronize with Gazebo's simulation clock. The /scan topic was remapped to the LiDAR's output, ensuring SLAM received real-time sensor data. To harmonize inputs from VO (/vo/odometry), IMU (/imu/data), and LiDAR (/scan), I implemented a message_filters.ApproximateTimeSynchronizer with a slop=0.2 seconds, accommodating minor timing mismatches between sensors.
- Initial real-time mapping in RViz revealed inconsistent occupancy grids, with phantom walls appearing in open fields. Debugging traced this to residual LiDAR noise and incorrect TF tree alignment. By refining the static transform from base_link to lidar_link and adjusting the LiDAR's <horizontal_samples> to 720 for higher resolution, the map fidelity improved significantly.
- After driving the robot through the Gazebo world to explore key waypoints, the map was saved using ros2 run nav2_map_server map_saver_cli -f farm_map. Cross-referencing the generated .pgm file with Gazebo's 3D geometry confirmed metric accuracy, with barn structures and crop rows aligned within 0.3 meters.
- To validate the full system, I executed a stress test: autonomous navigation between predefined GPS coordinates using the fused /odometry/filtered and live SLAM map. Sensor data was logged via ros2 bag record /odometry/filtered /gps/fix /map /scan for offline analysis.

- This task culminated in a fully integrated system capable of accurate localization and mapping in dynamic agricultural environments, meeting the project's precision requirements for autonomous farm operations.

Action Item 4: Visual-Inertial Odometry (VIO) and Sensor Fusion Techniques – 3 hour(s).

Research

- https://intra.ece.ucr.edu/~mourikis/papers/Li2013IJRR.pdf
- High-Precision, Consistent EKF-based Visual-Inertial Odometry
- Summary of Report
  - The paper addresses the challenge of motion tracking in GPS-denied environments using visual and inertial sensors. It focuses on estimating the vehicle trajectory using an inertial measurement unit (IMU) and a monocular camera without relying on a pre-existing map.
  - The authors present a detailed study of Extended Kalman Filter (EKF)-based Visual-Inertial Odometry (VIO) algorithms, comparing their theoretical properties and empirical performance. They highlight that traditional EKF formulations can be inconsistent due to incorrect observability properties, leading to underestimated uncertainties.
  - The paper demonstrates that the observability properties of the EKF's linearized system models do not match those of the underlying nonlinear system. This mismatch causes the filters to underestimate the uncertainty in the state estimates, leading to inconsistency.
  - MSCKF 2.0: Based on their analysis, the authors propose a novel, real-time EKF-based VIO algorithm termed MSCKF 2.0. This algorithm achieves consistent estimation by ensuring the correct observability properties of its linearized system model and performing online estimation of the camera-to-IMU calibration parameters.
  - The proposed MSCKF 2.0 algorithm is shown to achieve higher accuracy and consistency than even an iterative, sliding-window fixed-lag smoother, in both Monte Carlo simulations and real-world testing. The MSCKF 2.0 maintains computational efficiency suitable for real-time applications, making it practical for deployment in resource-constrained systems.
- Relation to Project
  - Relevance to GNSS-Visual Fusion and in developing a GNSS-Visual fusion system for autonomous farming robots, ensuring accurate and consistent state estimation is crucial. The insights from this paper on maintaining observability in EKF-based VIO systems directly inform the design of the fusion algorithm.
  - Implementation of Sliding Window Approach and the paper emphasis on a sliding window approach for pose estimation aligns with the need to manage computational resources effectively in real-time applications, which is pertinent to the farming robot's operational constraints.
  - The approach of performing online estimation of the camera-to-IMU calibration parameters is beneficial for the farming robot, which may experience changes in sensor alignment due to vibrations or environmental factors.
  - By adopting the MSCKF 2.0 algorithm, the fusion system can achieve improved consistency in state estimation, reducing drift and enhancing the reliability of the robot's navigation. The computational efficiency of the proposed algorithm ensures that it can be implemented on the farming robot's onboard systems without requiring excessive computational resources.
  - Robustness in GPS-Denied Environments and the algorithm's ability to maintain accurate state estimation in GPS-denied environments is particularly relevant for the farming robot, which may operate in areas with poor GPS coverage.
- Motivation for Research
  - Addressing Inconsistencies in EKF-based VIO and the need to overcome the limitations of traditional EKF-based VIO algorithms, which can be inconsistent due to incorrect observability properties, motivated the exploration of this paper.
  - Improving the accuracy of state estimation in the fusion system is essential for the precise navigation of the farming robot, especially in environments where GPS signals are unreliable.
  - The farming robot requires real-time processing capabilities. The proposed MSCKF 2.0 algorithm's computational efficiency makes it suitable for real-time applications, aligning with the project's requirements.
  - The ability to perform online calibration of the camera-to-IMU parameters ensures that the system can adapt to changes in sensor alignment, which is critical for maintaining accuracy over time. The algorithm's design allows for scalability, making it applicable to various robotic platforms beyond the farming robot, potentially benefiting other projects involving autonomous navigation.
  - This paper also lays foundation for future research with the insights gained from this paper provide a solid foundation for further research into advanced sensor fusion techniques and the development of more robust navigation systems for autonomous robots.

Action Item 5: Simulated Sensor Models and Their Impact on Robot Perception – 3 hour(s).

Research

- https://www.mdpi.com/407124
- A Systematic Review of Perception System and Simulators for Autonomous Vehicles Research
- Summary of Report
  - The paper presents a systematic review of perception systems and simulators used in autonomous vehicle (AV) research, categorizing perception systems into environment perception and positioning estimation systems.
  - It details the physical fundamentals, operating principles, and electromagnetic spectrum usage of common sensors such as ultrasonic, RADAR, LiDAR, cameras, IMU, GNSS, and RTK, highlighting their strengths and weaknesses.
  - The paper introduces spider charts to quantify sensor features across 11 parameters, aiding in the appropriate selection of sensors based on specific application requirements. It also discusses various simulation tools and platforms, including model-based development simulators, game engines, robotics field simulators, and AV-specific simulators, emphasizing their roles in testing and validating perception systems.
  - The authors highlight challenges in simulating perception systems, such as accurately modeling sensor noise, latency, and environmental conditions, which are critical for reliable testing. The paper provides an overview of current regulations concerning the implementation of autonomous vehicles in different countries, underlining the importance of compliance in AV development.
  - It emphasizes the need for integrating multiple perception systems to enhance the reliability and robustness of autonomous vehicles, advocating for sensor fusion approaches. The authors suggest future research directions, including the development of more sophisticated simulation environments and the standardization of testing protocols for perception systems.
- Relation to Project
  - The detailed analysis of various sensors aids in selecting the most appropriate sensors for the farming robot, balancing factors like cost, accuracy, and environmental suitability. Insights into simulation tools and challenges assist in setting up a realistic simulation environment for testing the robot's perception systems before field deployment.
  - The emphasis on integrating multiple perception systems supports the project's approach to combining GNSS, IMU, and visual data for robust localization. Recognizing the strengths and weaknesses of each sensor type helps in designing a system that compensates for individual sensor shortcomings, enhancing overall reliability.
  - Awareness of regulatory considerations ensures that the farming robot's perception systems adhere to relevant standards, facilitating smoother deployment and operation. The paper's insights contribute to developing comprehensive testing protocols for the robot's perception systems, ensuring thorough validation under various scenarios.
  - Understanding how different sensors perform under varying environmental conditions informs the design of the robot's perception system to maintain performance across diverse farming environments. The review provides a knowledge base for future enhancements to the robot's perception systems, including the integration of additional sensors or advanced simulation capabilities.
- Motivation for Research
  - Ensuring Perception System Reliability is critical for the autonomous operation of the farming robot. This paper offers comprehensive insights into designing and testing robust perception systems. Effective sensor fusion enhances localization accuracy. The paper's emphasis on integrating multiple perception systems aligns with the project's goals.
  - Before field deployment, thorough testing in simulated environments is essential. The paper guides setting up realistic simulations that accurately reflect real-world conditions. Farming environments can vary significantly. Understanding sensor performance across different conditions helps in designing adaptable perception systems.
  - Compliance with regulations is crucial for deploying autonomous systems. The paper's overview of regulatory considerations informs the project's development process.

Action Item 6: SLAM in Structured and Unstructured Outdoor Environments – 3 hour(s).

Research

- https://onlinelibrary.wiley.com/doi/abs/10.1002/rob.21831
- RTAB-Map as an open-source lidar and visual simultaneous localization and mapping library for large-scale and long-term online operation
- Summary of Report
  - RTAB-Map (Real-Time Appearance-Based Mapping) is an open-source SLAM (Simultaneous Localization and Mapping) library designed for real-time, large-scale, and long-term operations. Initially developed for appearance-based loop closure detection, it has evolved into a comprehensive SLAM solution supporting both visual and LiDAR data.
  - To handle large-scale environments efficiently, RTAB-Map implements a two-tier memory management

  - system comprising Short-Term Memory (STM) and Long-Term Memory (LTM). STM holds recent data for immediate processing, while LTM stores older data, which can be retrieved as needed. This approach ensures real-time performance without compromising mapping quality.
  - RTAB-Map is versatile in accommodating various sensor configurations, including monocular, stereo, RGB-D cameras, and 2D/3D LiDARs. It integrates odometry data from different sources, allowing for flexible deployment across diverse robotic platforms.
  - The system employs a bag-of-words approach for loop closure detection, enabling the identification of previously visited locations based on visual appearance. This mechanism is crucial for correcting drift in the estimated trajectory and maintaining map consistency over time.
  - RTAB-Map constructs a graph where nodes represent robot poses and edges represent spatial constraints derived from odometry and loop closures. Graph optimization techniques, such as g2o and GTSAM, are utilized to minimize errors and refine the map.
  - The paper presents extensive evaluations of RTAB-Map on various datasets, including KITTI, EuRoC, TUM RGB-D, and the MIT Stata Center dataset. These evaluations demonstrate the system's robustness and accuracy across different environments and sensor configurations.
  - Despite the complexity of SLAM operations, RTAB-Map maintains real-time performance through efficient memory management and optimized algorithms. This capability is essential for applications requiring immediate feedback, such as autonomous navigation.
  - RTAB-Map is fully integrated with the Robot Operating System (ROS), providing a suite of tools and packages for easy deployment and customization. This integration facilitates its adoption in various robotic applications and research projects.The system can generate both 2D occupancy grids and 3D point clouds, catering to different mapping requirements. This flexibility allows for detailed environment representation suitable for navigation and planning tasks.
  - RTAB-Map's design accommodates both structured environments, like indoor corridors, and unstructured outdoor settings, such as forests and fields. Its adaptability makes it a valuable tool for a wide range of SLAM applications.
- Relation to Project
  - In the context of autonomous farming, RTAB-Map's ability to handle both structured (e.g., greenhouses) and unstructured (e.g., open fields) environments aligns well with the diverse terrains encountered in agricultural settings. The system's support for various sensor types allows for the integration of existing hardware, such as RGB-D cameras and LiDARs, facilitating the development of a cost-effective SLAM solution for the farming robot.
  - Real-time performance is critical for dynamic farming operations. RTAB-Map's efficient algorithms ensure timely updates to the map, enabling responsive navigation and obstacle avoidance. Given the project's reliance on ROS, RTAB-Map's seamless integration simplifies the development process, allowing for straightforward implementation and testing within the existing framework.
  - In large farming areas, odometry drift can accumulate over time. RTAB-Map's loop closure detection helps correct this drift, maintaining accurate localization essential for tasks like planting and harvesting. The two-tier memory system ensures that the robot can operate over extended periods without overwhelming computational resources, which is vital for day-long farming activities.
  - The ability to generate 3D maps provides valuable data for analyzing terrain features, aiding in tasks such as irrigation planning and crop monitoring. RTAB-Map's open-source nature and modular design allow for customization to meet specific project requirements and scalability to accommodate larger farming operations.
  - A robust user community and comprehensive documentation provide support and resources, facilitating troubleshooting and further development. The system's validation against standard datasets offers confidence in its performance, providing a benchmark for evaluating the farming robot's SLAM capabilities.
- Motivation for Research
  - Autonomous farming requires reliable SLAM systems capable of handling diverse and dynamic environments. RTAB-Map's proven performance in various settings makes it a suitable candidate for this application. Farming robots often have limited computational resources. RTAB-Map's efficient memory management and real-time processing address these constraints effectively.
  - The project's use of ROS and standard sensors aligns with RTAB-Map's design, facilitating integration and reducing development time. Agricultural environments can change rapidly due to factors like weather and crop growth. RTAB-Map's adaptability ensures consistent performance under varying conditions.
  - Accurate localization is crucial for precision farming. RTAB-Map's loop closure and graph optimization techniques help maintain high localization accuracy. Farming tasks often require prolonged operation. RTAB-Map's design supports long-term mapping without degradation in performance.
  - The ability to handle multi-session mapping allows the robot to build upon previous maps, improving efficiency and reducing redundancy in data collection. As an open-source project with active development, RTAB-Map provides a platform for ongoing research and innovation in SLAM technologies applicable to agriculture.
  - Utilizing an open-source SLAM solution reduces software costs, making it more accessible for agricultural applications with budget constraints. RTAB-Map's extensibility allows for the addition of advanced features, such as semantic mapping and object recognition, enhancing the robot's capabilities in the future.

Action Item 7: Next week plan – 1 hour(s).

Project Work Summary

- Next week, I will focus on improving the quality and reliability of the IMU data within the simulation and ROS 2 environment. This includes thoroughly reviewing the IMU sensor noise parameters in the SDF to ensure realistic Gaussian noise modeling, verifying the correct frame alignment between the IMU and robot base, and testing the IMU data stream for consistency and latency.
- Building on the existing visual odometry node, I will work on enhancing feature detection robustness and matching accuracy under varying environmental conditions. This involves tuning ORB feature parameters, implementing dynamic match filtering to reduce false positives, and improving scale estimation by leveraging IMU accelerometer data more effectively.
- Integrating SLAM Toolbox with Visual-Inertial Odometry: I will integrate the SLAM Toolbox node into the existing launch system alongside the visual-inertial odometry node to enable real-time mapping and localization within the Gazebo farmland environment.
- Validating and Visualizing Sensor Fusion and Mapping: I will conduct comprehensive testing of the integrated system by driving the robot through predefined waypoints in the Gazebo simulation and recording sensor data streams. Using RViz2, I will visualize the fused odometry, IMU orientation, and SLAM-generated maps to assess the spatial accuracy and temporal consistency of the system.
- Preparing for Real-World Deployment and Robustness Testing: To bridge the gap between simulation and real-world application, I will design robustness tests that simulate sensor failures, noise spikes, and environmental changes within Gazebo. This includes introducing artificial GNSS outages, IMU bias drifts, and visual occlusions to evaluate the system’s fault tolerance and recovery capabilities.

Action Item 8: Report writing – 1 hour(s).

Project Work Summary

- Created word document layout to write contents of the weekly progress.
- Created relevant subsections in the epicspro website and documented 20 hours of weekly progress.
- Collected relevant documents research papers, relevant links and company's objective from their portal.