EBS221 Final Project Report

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1 Introduction

This project developed an autonomous orchard navigation system integrating bicycle model dynamics, Extended Kalman Filter (EKF) state estimation, LiDAR-based mapping, tree detection, and advanced path planning using pure pursuit control with genetic algorithm optimization.

2 System Architecture

2.1 Vehicle Model

The autonomous platform utilizes an Ackermann-steered vehicle with the following specifications:

- **Wheelbase (L):** 3 meters
- **Width:** 2 meters
- **Steering Limit:** 55 degrees
- **Control Dynamics:** First-order lag ($\tau_\gamma = 0.1$s, $\tau_v = 0.1$s)

3 Methodology

3.1 Task 1: Sensor Covariance Estimation

A calibration sequence using a figure-8 pattern was executed to estimate sensor noise characteristics.

3.2 Task 2: Extended Kalman Filter Implementation

The EKF implementation uses:

- **State Vector:** $\mathbf{x} = [x, y, \theta]^T$ (position and orientation)
- **Prediction:** Bicycle model kinematics with odometry measurements
- **Correction:** GPS/compass measurements every 1 second
- **Median Filter:** 5-point window for LiDAR noise reduction

Note on Sensor Simulation

While developing and testing the EKF and perception modules, we encountered challenges using the provided `robot_odo.p`, `LaserScannerNoisy.p`, and `GPS_CompassNoisy.p` simulation functions. These modules produced erratic or inconsistent results in our environment. As a result, we implemented our own noisy odometry, LiDAR, and GPS/compass wrappers with tunable Gaussian noise models. These custom functions allowed us to better control noise levels and ensure consistency during testing and validation of our navigation pipeline.

3.3 Navigation Strategy

3.3.1 Phase 1: Intelligent Perimeter Scan

- Route: $(0,0) \rightarrow (0, Y_{max}) \rightarrow (X_{max}, Y_{max})$
- Real-time tree detection during scan
- Adaptive trajectory modification based on tree block detection

3.3.2 Phase 2: Column-wise Tree Block Traversal

- **Entry Strategy:** Southeastern corner approach using minimum turning radius $R_{min} = L/\tan(\gamma_{max})$
- **Pattern:** Alternating north-south columns with U-turns
- **Control:** Segmented pure pursuit with dual lookahead distances:
  - Straight segments: $L_d = 4.0$m
  - Turn segments: $L_d = 2.0$m

3.3.3 Phase 3: GA-Optimized Return

- Cost matrix incorporating Euclidean distance and tree avoidance
- Greedy TSP solution for computational efficiency
- Strategic waypoints for optimal path planning

4 Results

4.1 Covariance Matrix

The estimated covariance matrices are:

Odometry Covariance Matrix (Q):

$$Q = \begin{bmatrix} 1.0078 \times 10^{-4} & 0 \\ 0.0 & 2.4130 \times 10^{-5} \end{bmatrix} \tag{1}$$

GPS/Compass Covariance Matrix (R):

$$R = \begin{bmatrix} 14.32 & 1.00 & 0.0 \\ 1.00 & 10.18 & 0.0 \\ 0.0 & 0.0 & 0.017 \end{bmatrix} \tag{2}$$

4.2 Tree Detection Results

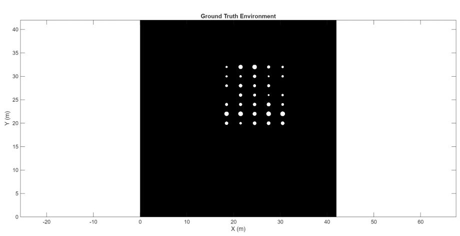
Metric	**Value**
Ground Truth Trees	35 trees
Detected Trees	35 trees
Detection Rate	100.0%
Precision	100.0%
Mean Position Error	0.42 meters
Mean Diameter Error	0.08 meters

Table 1: Tree Detection Performance

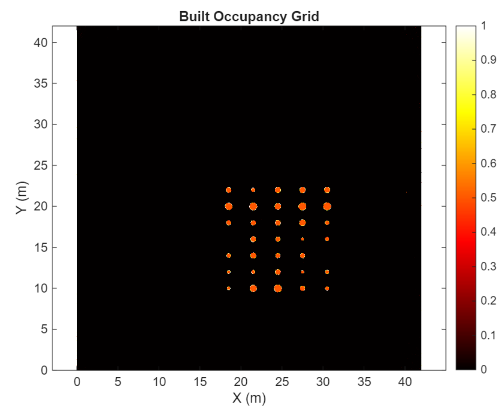
4.3 Error Statistics Summary

Metric	Value
Mean Diameter	0.474 m
Standard Deviation	0.170 m
Min Diameter	0.194 m
Max Diameter	0.800 m
RMS	0.504 m
95th percentile	0.762 m

Table 2: Perceived Environment Statistics

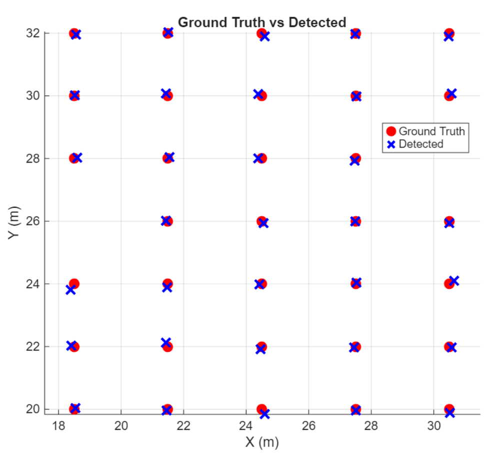


(a) Ground truth orchard environment

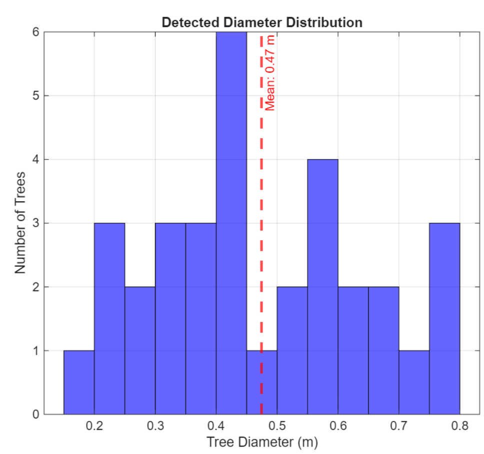


(b) Real-time occupancy grid building

Figure 1: Environment and Navigation Visualization



(a) Tree detection map



(b) Detected tree diameter distribution

Figure 2: Detection Performance

Table 3: Tree Detection Data (33 trees detected)

Tree ID	X Coordinate (m)	Y Coordinate (m)	Diameter (m)
1	18.3981	22.0262	0.6871
2	18.5485	20.0334	0.5837
3	18.3899	23.8184	0.1939
4	18.5220	30.0265	0.3682
5	18.5556	31.9526	0.2046
6	18.5955	28.0350	0.3259
7	21.4414	22.1198	0.7335
8	21.5190	32.0405	0.7604
9	21.4410	26.0085	0.5778
10	21.5553	28.0408	0.5774
11	21.4662	23.8833	0.4254
12	21.4537	19.9675	0.4008
13	21.4410	30.0682	0.3108
14	24.6043	31.9020	0.6176
15	24.4609	21.9133	0.5903
16	24.3876	30.0602	0.4429
17	24.4172	23.9878	0.5310
18	24.3898	28.0038	0.4847
19	24.5496	25.9403	0.4298
20	24.5856	19.8355	0.3398
21	27.4532	21.9636	0.8000
22	27.5152	19.9689	0.6183
23	27.5247	24.0471	0.6595
24	27.4805	31.9713	0.5449
25	27.4712	27.9332	0.4284
26	27.4890	26.0010	0.3937
27	27.5231	29.9899	0.2872
28	30.5699	21.9703	0.7632
29	30.5129	19.8749	0.4500
30	30.4685	31.8933	0.2806
31	30.4961	25.9457	0.3606
32	30.5655	30.0755	0.2390
33	30.6469	24.1028	0.2435