Masters Thesis Information Showcase
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Department: Computer & Information Systems Engineering
Programme: Masters of Science
Specialization: Artificial Intelligence

1	**Title of the Thesis:** Adaptive Multi-Sensor Fusion for Robust Localization of Mobile Robots in GPS-Denied Environments
2	**Abstract** (min 300 to 500 words) Autonomous navigation in GPS-denied environments remains one of the most critical unsolved challenges for mobile robots operating in urban canyons, tunnels, underground parking structures, and indoor spaces. As cities grow denser and autonomous systems - delivery robots, self-driving vehicles, inspection platforms become integral to urban infrastructure, the inability to localise reliably without GPS constitutes a fundamental barrier to safe and sustainable deployment. This thesis addresses that barrier through three tightly linked contributions. The first contribution is CARLA-GDN, a new multimodal dataset collected using the CARLA autonomous driving simulator (version 0.9.16) on an Azure NC16as T4 virtual machine. The dataset comprises 8.75 hours of synchronised sensor recordings across nine urban and mixed-terrain environments, spanning four GPS degradation regimes: full GPS (R0), degraded (R1), severe (R2), and full denial (R3). Each timestep provides paired ground-truth and degraded GPS coordinates alongside IMU (accelerometer and gyroscope), 32-beam LiDAR, and Doppler radar streams, yielding 4.47 million timesteps and 2.78 million clean sensor readings. This is the first structured benchmark dataset that deliberately and controllably varies GPS quality across all four regimes under identical sensor and environmental conditions. The second contribution is the first comprehensive cross-paradigm benchmark of nine navigation methods under these controlled conditions. The methods span three paradigms — traditional filtering (dead reckoning, controlled integrator, Kalman filter), tree-based learning (linear regression, HistGradientBoosting), and deep learning (LSTM, GRU, 1D-CNN). Under full GPS denial, HistGradientBoosting (HGB) achieves the lowest RMSE of 126.8 metres, outperforming dead reckoning by 37.5% and deep learning architectures by 55%. Contrary to expectations, LSTM, GRU, and CNN perform no better than assuming the robot never moves. The benchmark also uncovers a novel anisotropy reversal: position error is X-dominant under full GPS (X/Y ratio = 1.304) but shifts to Y-dominant under full denial (ratio = 0.724), a previously undocumented phenomenon with direct implications for sensor fusion design. The third and central contribution is CASFA (the Context-Aware Sensor Fusion Architecture) - a five-layer adaptive framework that directly addresses the limitations exposed by the benchmark. Layer 1 classifies the current GPS regime in real time using only non-GPS sensors, achieving 99.84% accuracy. Layer 2 applies anisotropic per-axis sensor weights learned separately for X and Y via R^2 cross-validation, directly exploiting the regime-dependent error anisotropy. Layer 3 uses regime-specialised HGB predictors,

	each optimised for the statistical characteristics of its regime. Layer 4 blends outputs through confidence-weighted fusion with a baseline guard that prevents regression when HGB already performs well. Layer 5 applies Kalman smoothing to remove high-frequency jitter. Across all sessions, CASFA reduces trajectory RMSE by up to 74.3% compared to the best fixed method under full denial, while the baseline guard prevents performance degradation under full GPS conditions. Ablation studies confirm that each layer contributes measurable and statistically significant improvement, with the regime classifier and anisotropic weighting providing the largest individual gains.
3	**Impact on Sustainability of Urban Regions or SDG-11 "Sustainable Cities and Communities"** (min 500 words) United Nations Sustainable Development Goal 11 calls for cities and human settlements to be inclusive, safe, resilient, and sustainable. At the heart of this goal lies a practical challenge: the physical infrastructure of a city - its roads, transit corridors, emergency networks, and logistics systems must function reliably for every resident, in every condition. This thesis contributes directly and concretely to that vision through four distinct pathways. **1. Enabling Safe and Efficient Urban Mobility (SDG Target 11.2)** SDG Target 11.2 calls for safe, affordable, accessible, and sustainable transport systems for all, with specific emphasis on road safety and the expansion of public transport. Autonomous vehicles and delivery robots are increasingly central to how forward-looking cities plan to meet this target — extending last-mile connectivity, reducing private vehicle congestion, and providing mobility services to people who cannot drive. The critical barrier to deploying these systems at scale in real cities is reliable localization. An autonomous vehicle entering a tunnel on a major urban artery, or a delivery robot navigating a downtown street flanked by skyscrapers, loses GPS entirely or receives signals corrupted by multipath reflections with errors exceeding 50 metres. This thesis quantifies that problem precisely and solves it adaptively. CASFA's 74.3% RMSE reduction under full GPS denial means a system that previously lost track of vehicle position by half a city block can now maintain localisation within a corridor narrow enough for safe lane-level navigation. For city planners and transport authorities, this is the difference between a deployment that works and one that does not. The CASFA architecture achieves this without adding new sensors or requiring modified urban infrastructure, it operates on the same IMU, LiDAR, and radar hardware already present in modern autonomous platforms. **2. Supporting Infrastructure Inspection and Disaster Resilience (SDG Targets 11.5 and 11.B)** SDG Target 11.5 addresses reducing deaths and economic losses from disasters; Target 11.B calls for integrated resilience policies. Both require that emergency and inspection systems function precisely where GPS fails most severely: collapsed structures, flooded tunnels, underground utilities, and disaster-affected dense urban areas where satellite signal infrastructure may itself be damaged. When a tunnel floods, when a building collapses, or when an underground utility ruptures, the first operational question is: where exactly is the problem? Robotic inspection platforms offer a safer alternative to sending human inspectors into structurally compromised or smoke-filled environments — but only if they can navigate without GPS. CASFA's regime classifier, operating exclusively on non-GPS sensors, achieves 99.84% accuracy in identifying the current signal environment and

adapting fusion strategy accordingly. In the full denial regime — the tunnel, the underground parking structure, the disaster-damaged building — CASFA's regime-specialised predictors and confidence-weighted blending keep localisation errors bounded where every other tested method diverges. Furthermore, the CARLA-GDN dataset, released publicly on Kaggle, provides the first controlled benchmark resource spanning all four GPS degradation regimes, enabling researchers worldwide to develop and validate navigation systems for inspection robots and disaster-response platforms without requiring expensive physical test infrastructure.

3. Reducing Urban Air Pollution Through Autonomous Last-Mile Logistics (SDG Target 11.6)

SDG Target 11.6 focuses on reducing the adverse per-capita environmental impact of cities, including air quality. A significant contributor to urban air pollution is last-mile delivery: vans and motorcycles circulating through city centres, making short trips that are disproportionately fuel-intensive per kilometre and producing concentrated emissions in high-density residential and commercial areas. Autonomous ground robots offer a compelling alternative like electric, fleet-optimised, and capable of serving multiple drop points without a driver. That vision depends, however, on robots that work reliably in actual urban environments. A delivery robot operating on a street between office towers, crossing a covered walkway, or accessing an underground loading bay will face GPS degradation constantly throughout a normal delivery cycle. If its localisation system cannot handle those transitions gracefully, the deployment fails economically and operationally. CASFA is specifically designed for exactly this heterogeneous signal environment. Its five-layer architecture handles the transition from full GPS in open areas to severe degradation in urban canyons to full denial underground seamlessly, without manual intervention, and without sensor hardware upgrades. By making it more technically feasible to deploy autonomous ground robots reliably in urban environments, this research directly supports the case for substituting high-polluting last-mile delivery with cleaner autonomous alternatives, contributing measurably to SDG Target 11.6.

4. Original Technical Finding With Direct Urban Planning Relevance

This thesis's anisotropy reversal finding — that position error is X-dominant under full GPS (X/Y ratio = 1.304) but becomes Y-dominant under full denial (ratio = 0.724) — has direct implications for how autonomous systems should be deployed in cities and how urban corridors should be mapped for autonomous navigation. The Y-axis in vehicle-frame coordinates corresponds to lateral positioning: staying in lane, avoiding kerbs and pedestrians. In an urban canyon, the cross-street GPS error can be three to ten times the along-street error due to multipath reflections off building facades. This means a vehicle's GPS may report a position placing it on the pavement or in an adjacent lane — a safety-critical failure in dense pedestrian environments. CASFA directly addresses this through its anisotropic weighting layer: separate sensor weight vectors are learned for the X and Y axes, per regime, so that the lateral position estimate is protected from GPS-induced drift in exactly the conditions where it matters most. This is, to the best of the authors' knowledge, the first navigation architecture to explicitly exploit the direction-dependency of GPS error anisotropy in urban environments. For transport authorities and autonomous vehicle operators, this finding provides concrete quantitative guidance on where the hardest

	localisation challenges are and how they can be addressed through software adaptation rather than costly infrastructure change. **5. Open Science Contribution to the Global Urban Research Community** SDG 11 is not achievable by individual actors — it requires shared knowledge, shared tools, and shared benchmarks. The CARLA-GDN dataset, released publicly on Kaggle as part of this thesis, contributes directly to that commons. It is the first structured, controlled benchmark for GPS-denied urban navigation spanning four degradation regimes with synchronised multimodal sensor data across nine simulated environments and multiple weather conditions, including rain, fog, and storm. This dataset enables researchers in cities across the world — including those without access to expensive autonomous vehicle test fleets or urban proving grounds — to develop and evaluate localisation algorithms for urban robotic systems on a level playing field. By democratising access to this benchmark, the thesis lowers barriers to research on a problem that disproportionately affects dense, resource-constrained cities where the need for autonomous mobility is greatest but research infrastructure is most limited. Additionally, the benchmark itself — the first cross-paradigm evaluation of nine navigation methods under identical conditions — provides the field with a replicable methodology for evaluating future navigation systems, which is a contribution to research quality and comparability that will compound in value as the autonomous systems community continues to grow. In aggregate, this thesis advances SDG-11 through multiple reinforcing pathways: improving the technical feasibility of autonomous urban transport; enabling robotic operation in disaster-response and infrastructure-inspection contexts; supporting the case for cleaner autonomous logistics; producing an original city-level finding on GPS error anisotropy; and releasing an open dataset and benchmark that equips the broader global research community. Together, these contributions address the technical foundation that sustainable, resilient, and inclusive cities will need as autonomous systems become part of their operational fabric.
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6	**Graphical Abstract** The graphical abstract below illustrates the end-to-end CASFA pipeline for GPS-denied robot navigation:

INPUT SENSORS

IMU (Accel + Gyro) · 32-beam LiDAR · Doppler Radar · Degraded GPS

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LAYER 1 — Regime Classifier

Classifies GPS environment into R0 / R1 / R2 / R3 - Accuracy: 99.84%

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LAYER 2 — Anisotropic Per-Axis Sensor Weighting

Separate X and Y weight vectors per regime - Addresses anisotropy reversal (X/Y ratio: 1.304 → 0.724)

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LAYER 3 — Regime-Specialised HGB Predictors

Separate HistGradientBoosting models trained per GPS regime, Best single-method RMSE: 126.8 m

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LAYER 4 — Confidence-Weighted Blending + Baseline Guard

Blends estimator outputs by confidence - Guard prevents regression when baseline already accurate

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LAYER 5 — Kalman Smoothing

Removes high-frequency jitter - Final smoothed position estimate

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OUTPUT — Adaptive Position Estimate

Up to 74.3% RMSE reduction vs. best fixed method - Robust across all 4 GPS regimes

Key Result: CASFA achieves up to 74.3% trajectory RMSE reduction under full GPS denial compared to the best fixed baseline (HistGradientBoosting at 126.8 m RMSE), validated across 8 sessions and confirmed by bootstrap 95% confidence intervals. The benchmarking component — the first cross-paradigm evaluation of 9 navigation methods (dead reckoning, controlled integrator, Kalman filter, linear regression, HistGradientBoosting, LSTM, GRU, CNN, and naive baseline) — establishes that deep learning architectures provide no measurable benefit over simple baselines in this setting, making CASFA's regime-aware tree-based adaptive approach both technically superior and computationally efficient.

Dataset: CARLA-GDN - 8.75 hours, 4.47 M timesteps, 9 urban environments, 4 GPS regimes is publicly available on Kaggle.