School of Electrical, Electronic, and Computer Engineering

GENG5512 Engineering Research Project Report

A Robust Localisation Framework for Autonomous Applications in Urban Environments

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Word Count: 6384
Submitted: 17 October 2021

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1. Abstract

Autonomous vehicle applications depend on reliable and accurate navigation data in order to facilitate safe driving behaviour. To this end, Global Navigation Satellite Systems (GNSS), Inertial Navigation Systems (INS), and Simultaneous Localisation and Mapping (SLAM) algorithms are widely employed, however with each of these approaches comes drawbacks and weaknesses. Of particular note, urban environments have a detrimental impact on many sensor technologies, exhibiting many effects that can severely degrade the navigation performance of GNSS, INS, and SLAM based platforms.

This research explores the shortcomings of various navigation sensors and proposes a framework for achieving accurate and reliable navigation through a loosely coupled fusion scheme utilising GNSS, INS, and SLAM based localisation subsystems.

Experimentation demonstrates that while Real Time Kinematic (RTK) aided GNSS can provide highly accurate long-term positioning it is vulnerable to prolonged outages and performance degradation in heavily developed urban areas. GNSS is also prone to bias errors with can result in a significant offset between the sensors reported and true positions. In contrast, INS solutions are largely immune to external environmental influences, however they suffer from integration drift, accumulating error over time, making them unsuitable for maintaining accurate long-term navigation. SLAM systems

are effective at correcting for drift and bias errors in other sensors, but SLAM performance is heavily dependent on the presence of distinguishable features in the surrounding environment. The fusion of sensor readings from a variety of complementary sensors presents a mechanism by which the drawbacks of individual sensors can be compensated for to maintain navigation performance in a variety of operating conditions.

The solution proposed fuses GNSS, INS, and SLAM observations to form a robust navigation system that is optimised for ground-based navigation in urban environments. Trials were performed on the nUWAy shuttle bus, UWAs own experimental autonomous automotive vehicle platform, with early experimental results demonstrating promising localisation performance from the data fusion scheme developed on the platform. The results have demonstrated robust position and orientation tracking when navigating the challenging urban surrounds of the UWA campus.

2. ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor Thomas Bräunl, without whom this project would not have been possible. He has provided valuable insight, advice, and direction throughout the project and I am much obliged to him for the time he has invested in supervising this project. I would also like to thank the rest of the nUWAy team for their contributions to the project. I would like to specifically acknowledge Jai Castle, Lemar Haddad, Thomas Copcutt, and Kieran Quirke-Brown for their invaluable working getting the project to where it is today. Finally, I would like to thank the rest of the REV team, specifically Thomas Drage and Robert Reid for the expertise and advice that they provided.

3. INTRODUCTION

RECENT advances in autonomous driving technology have led to the growing adoption of sophisticated intelligent driving systems with many automotive vehicles on the road today now including semi-autonomous driver assistance systems as standard features. Provides current trends continue, the next generation of intelligent vehicles is set to become feature increasingly more advanced automation, to the point where true Autonomous Vehicle (AV)s requiring little to no operator interaction may soon become commonplace.

Instrumental to the success of autonomous driving is localisation, the process of establishing and tracking the position and orientation of a mobile platform with respect to its environment. In AV applications it is critical that localisation be robust and accurate to the ensure safe guidance and control. Current vehicular localisation techniques are dominated by the use of Global Navigation Satellite System (GNSS), with modern systems capable of providing centimetre precision localisation. However, GNSS performance can be severely degraded in dense urban environment where large building occluded satellites from view and multipath effects induce measurement error preventing the GNSS receiver from obtaining an accurate fix.

There is a thus a need to develop localisation techniques that are robust and reliable in order to facilitate the safe operation of autonomous vehicles in urban environments.

3.1 Background

The Renewable Energy Vehicle (REV) project team has been developing nUWAy, an autonomous driving solution based on a modified EasyMile EZ10 [3] that was purchased second hand. Intended to operate on the internal roads and pathways of the University of Western Australia (UWA) campus, the nUWAy shuttle is an electric shuttle bus fitted with a comprehensive sensor suite including a differential GNSS receiver, standalone Inertial Navigation System (INS) unit, and is fitted with multiple LIDARs and cameras providing wide angle front and rear perception data that can be leveraged to aid in navigation and obstacle avoidance tasks. Computation can be performed on board the vehicle using two computers installed in the vehicle. The control software of the vehicle is being actively developed by a student led team.

Fig. 1: The nUWAy shuttle bus.

The main UWA campus, locate in Crawley, WA, presents a challenging navigation environment as navigating the narrow campus pathways depends highly accurate localisation while large buildings and heavy foliage in the area detrimentally impact sensor performance. The nUWAy electric shuttle bus thus serves as an excellent testbed for developing a highly robust localisation framework for AV applications.

4. Aims and Objectives

The scope of this project is to develop and test a sensor fusion and data processing pipeline to accurately localisation and track an autonomous platform.

The project will utilise the nUWAy bus as a test vehicle for the localisation system with testing being performed on the UWA campus. The project aims to develop a system that utilises GNSS, INS, and LIDAR observations for localisation and the system should be optimised to perform reliably in an urban environment, specifically that of the UWA campus. Fundamentally, this project will evaluate techniques for maintaining robust and accurate localisation in the presence of unreliable sensor observations. Specifically, this project aims to develop a system that:

1) Fuses data from multiple sensors to produce a single fused pose estimate.
2) Minimises and corrects for accumulated estimation errors over time.
3) Estimates positional uncertainty for use in navigational decision logic.

5. Literature Review

5.1 Localisation

5.1.1 Global Navigation Satellite System

GNSS operates by observing signals from navigation satellite constellations to obtain pseudo-range measurements from which the system may estimate its position anywhere around the globe. As of 2021 there are currently four fully operational GNSS constellations: the USA's NAVSTAR GPS, the Russian GLONASS, Europe's Galileo, and China's BeiDou [4] network. Baseline GNSS systems provide accurate measurements to within 10 m. With the aid of Real time Kinematic (RTK) corrections from a nearby base-station, a GNSS system can provide measurements with 1cm accuracy rendering such augmented systems suitable for precise localisation [5]. However, pure GNSS localisation of autonomous vehicles operating in urban environments is often unreliable, as in such environments buildings and structures tend to reflect and block GNSS signals, degrading positional certainty or causing total GNSS denial [6].

5.1.2 Inertial Measurement Unit

An Inertial Measurement Unit (IMU) measures the acceleration and orientation of a platform using accelerometers and gyroscopes, and magnetometers. As the unit does not rely on external references, an IMU can be used for dead reckoning in almost any environments. However, IMUs suffer from accumulative drift, becoming less accurate over time [7]. IMU sensor drift is conventionally corrected by fusing IMU readings with GNSS observations in an INS. A recent innovation in the field proposes a solution that intelligently corrects for IMU drift by exploiting the kinematic assumptions that underpin the system, using them to determine and correct for IMU sensor biases [8].

5.1.3 SRF Laser Odometry

Symmetric Range Flow (SRF) laser odometry is a LIDAR scan matching odometry algorithm based on 2D planar laser scans [9]. It operates by estimating the relative motion between consecutive LIDAR scans. Since laser odometry gives relative position and velocity estimates it cannot be utilised to determine the absolute position of a platform. As with any LIDAR based system, laser odometry requires that the environment have sufficient detectable features visible in the scans.

5.1.4 Google Cartographer

Google cartographer is a software package that can perform 2D or 3D Simultaneous Localisation And Mapping (SLAM) using data from LIDAR scan data. Cartographer takes a scan-to-map approach performing a pose graph optimisation on laser scans to avoid the use of a computationally expensive particle filter [10]. Like all SLAM systems Cartographer produces a map of the environment while simultaneously locating the robot within the generated map. Since SLAM generates a map of the robot's surroundings is often used to produce cost maps for obstacle avoidance path planning systems [11].

5.1.5 SLAM Toolbox

SLAM Toolbox is a set of tools for 2D LIDAR based SLAM build by Steve Macenski and is the primary SLAM library supported by ROS2. It is a heavily modified extension of the `open_karto` library that adds support for 'lifelong' mapping which allows the user to create and update existing maps, then reload the data for use in subsequent mapping sessions [12]. As with Cartographer, SLAM

Toolbox is based on pose graph optimisation and uses an improved version of the Cartographer's Ceres scan matcher.

5.2 Sensor Fusion

5.2.1 Unscented Kalman Filter

The Kalman Filter is a statistical filter that uses an internal system model to fuse sensor observations. Commonly applied in sensor fusion to produce a unified state estimate from one or more noisy sensors the Kalman filter is considered to be the de facto standard method tool for sensor fusion. The basic Kalman filter is limited in its applications as it cannot operate on non-linear systems. The Unscented Kalman Filter (UKF) is enhancement of the classical Kalman Filter that extends the filter to non-linear systems. In the UKF a minimal set of sample points are propagated through the non-linear functions to produce a new set of points from which an updated mean and covariance are calculated [13]. Of the various Kalman Filter extensions, the UKF often demonstrates the best performance in non-linear estimation scenarios.

5.2.2 Urban Map Matching

In regions where geo-referenced building footprints are available, LIDAR point clouds may be matched to building features, providing a mechanism by which LIDAR observations can be orientated and positioned with respect to the global reference frame [14].

5.2.3 Adaptive Filtering

In typical Kalman Filter applications measurement and process covariances are predefined static values. Since GNSS performance is mainly impacted by environmental factors the measurement variance of GNSS readings is dynamic [15]. Adaptive Kalman Filters dynamically recompute measurement covariance through the application of statistical methods to previous observations [15]. Contextual information about current GNSS status can be used to assist in dynamically adjusting the adaptation process [16].

5.2.4 Context-aided GNSS/IMU Fusion

Erroneous GNSS position updates will degrade localisation accuracy if not accounted for. An adaptive filter framework such as the adaptive Kalman Filter can reject outlier data points that are not strongly correlated with the current pose estimate [17]. However, these filters fail to detect and mitigate biased sensor drift that can be caused by multipath interference [18].

To address this problem map-aided fusion using pre-existing or dynamically generated environment maps can be applied to dynamically weigh and filter GNSS position fixes, eliminating fixes that are implausible or impossible given the surround terrain. Map-aided fusion applies map constraints under the assumption that the tracked subject is limited to specific map regions to detect and correct for improbable measurements [18].

Further context aided correction can be made in autonomous driving contexts as additional contextual information is available in the form of commanded vehicle motions. This contextual information can be used to enhance the received sensor data by correcting for gyroscope and accelerometer bias when the vehicle is stationary [19].

5.3 Safety

5.3.1 ISO 26262

ISO 26262 is an international standard that prescribes the functional safety requirements for automotive electrical and electronics systems. The standard provides a risk-based approach to categorising and managing safety hazards in automotive systems [20].

ISO26262 defines four safety levels, Automotive Safety Integrity Level (ASIL) A-D, based on the probability, controllability, and severity of a failure. Safety requirements are assigned an ASIL rating, with level D requiring the most stringent testing and safety processes [21].

5.3.2 Receiver Autonomous Integrity Monitoring

Since the late 1980s Receiver Autonomous Integrity Monitoring (RAIM) has been adopted in the aviation industry, performing consistency checks to monitor the integrity of received GNSS measurements. RAIM facilitates the alerting of abnormal sensor conditions allowing for corrective action to be taken when GNSS integrity is compromised.

While effective in aviation, traditional RAIM approaches do not take multipath effects and limited satellite visibility into account rendering them poorly suited to urban contexts [22]. Instead, Automotive applications typically employ a hybridised approach that combines data from other sensors to produce an improved measure of system integrity.

6. Design Process

6.1 Previous Work

Prior to starting work on this project, the nUWAy shuttle employed a previously developed localisation system based on ROS1 and Google Cartographer. While functional, this system had several significant limitations:

1) Localisation quality was highly dependent on having an accurate initial pose estimate which had to be entered manually by the operator.
2) Cartographer required data from every configured LIDAR to operate; in the event of a single sensor failure the system would fail.
3) Cartographer's localisation estimate would drift over time.
4) While the platform was fitted with a GNSS receiver it was not being utilised for localisation.

6.2 Requirements

The solution developed needs to be capable of localising the platform with respect to a generated navigation map of its local environment. Furthermore, it is required to maintain accurate 2D tracking of the platform within the aforementioned map under normal operating conditions. The systems is also required to meet the robustness criteria of resilience to sensor disruptions and performance degradation. It is additionally required to re-localise on start-up without the need for human intervention. The design should be optimised for operation in urban environments where frequent GNSS disruptions and highly variable surroundings are to be expected.

6.3 Constraints

6.3.1 Hardware

Due to budget constraints, there was limited scope to purchase new hardware for the project. Notably the two computers on available on the nUWAy platform were not designed for heavy computational loads, restricting the complexity of the code that can be run onboard the platform. This constraint placed a limit on the mapping resolution that could be used for SLAM and limited the refresh rate that the system could reliably sustain.

Additionally, while the bus is equipped with wheel position encoders that can be used for odometry, they were inaccessible preventing their use within the localisation stack.

6.3.2 External Factors

There were several external factors that delayed the project and consequently, due to time constraints, limited the scope of the project.

COVID-19
: The COVID-19 pandemic was ongoing during the course of the project and intermittent lockdowns prevented physical work on the project. These lockdowns delayed testing and limited the time available for development work.

Steering failure
: During the course of the project the vehicle's rear steering mechanism failed rendering the platform temporarily inoperative. Consequently, research work was halted for several weeks in order to diagnose and repair the platform. At the time of writing this issue has not yet been resolved although a workaround has been developed that allows the vehicle to be operated, albeit with degraded manoeuvring characteristics.

4G sim expiry
: Internet connectivity is provided to the platform via a 4G modem. During Semester 2, 2021, the existing Telstra mobile data subscription expired which rendered the platform without network connectivity until a new sim card was procured and installed.

6.4 Tools

6.4.1 ROS2

The nUWAy navigation stack is built on top of Robot Operating System (ROS). ROS is a flexible toolkit of modular software libraries and tools with a common message passing mechanism designed for developing robot control software [23]. Using ROS allows existing device drivers and software modules to be integrated into the localisation system which facilitates the rapid prototyping of the localisation system.

6.4.2 NovAtel GNSS

The bus is fitted with an NovAtel GNSS receiver. There exists a ROS driver for NovAtel devices that can output both raw data from the device and ROS 'NavSatFix' messages [24]. This receiver is capable of using RTK correction data to provide centimetre precision accuracy [25]. RTK corrections are provided via the AUSCORS Network Transport of RTCM via Internet Protocol (NTRIP) Broadcaster, a public, government run RTK feeder service [26]. As NTRIP is an internet-based protocol it requires a constant internet connection to function. In the event of a network outage positional accuracy will degrade, impacting localisation performance.

6.4.3 LIDAR

The LIDARs onboard the nUWAy shuttle are network connected and provide symmetric wide-angle coverage to the front and rear of the platform. ROS drivers for the LIDARs publish the LIDAR data as standardised 'pointcloud2' messages which contain the collection of 3D points that compose a single scan. Most SLAM systems require these point clouds to be flattened into a 2D scan before they can be utilised.

6.4.4 Xsens INS

The Xsens MTi-G-710 installed on the shuttle bus is an INS module with both GNSS and IMU sensors that are internally fused using a modified Kalman Filter. The internal filter additionally provides correction for transient accelerations and magnetic disturbances [27]. There is a ROS driver available that publishes sensor readings and pose estimates as ROS messages that can be utilised by other ROS nodes. In the event that the module loses its GNSS signal it falls back to pure IMU mode where it only outputs velocity and acceleration data [27].

6.4.5 SBG Systems INS

During the design process it quickly became apparent that the existing sensor suite did not have any suitable means of determining the absolute heading of the platform and that the existing inertial measurement sensors would be unsuitable as a localisation source. Efforts were made to find another sensor that could be used as a substitute and eventually the project group was able to procure an SBG Systems (hereafter shortened to SBG) Eclipse-D INS unit through a sponsorship deal with the manufacturer.

TABLE I: Comparison between the Xsens and SBG INS units [1], [2]

Model	Xsens Mti-710	SBG Eclipse-D
Roll & pitch precision	0.2°	0.05°
Heading precision	0.8°	0.2°
Position accuracy	1.0 m	0.01 m
velocity accuracy	$0.05\,\mathrm{m\,s^{-1}}$	$0.03\,\mathrm{m\,s^{-1}}$
GNSS antennas	single	dual
GNSS RTK	no	yes
Heading source	magnetic	GNSS

The SBG unit has several distinct advantages that make it more suitable for urban applications than the Xsens unit. Higher quality inertial sensors and RTK capable GNSS provide more accurate position tracking while the internal dual antenna GNSS allows the unit to derive heading information from GNSS readings instead of relying on magnetic orientation.

6.4.6 Sensor Fusion

The UKF is preferred over other Kalman Filter variants as is exhibits the better non-linear performance than other alternative filters. The 'robot_localization' ROS package implements a UKF that can handle multiple GNSS, IMU, and odometry sources [28]. The implementation gracefully handles missing sensor data making it robust to sensor failure and degradation.

When designing a Kalman Filter, it is generally recommended to use a specific process model that accounts for the specific vehicle dynamics of the target platform as this can produce better state estimates [29]. A major limitation of the 'robot_localization' package is that it uses a standard constant acceleration kinematic model derived from Newtonian mechanics and does not account for specific vehicle dynamics.

6.5 Evaluation Framework

The evaluation process was based on a mixture of qualitative and quantitative observations taken during practical trials of the experimental platform. GNSS, INS, and UKF performance was primarily measured used quantitative measures but SLAM performance, due to the design of the algorithm, was difficulty to measure quantitatively and thus qualitative evaluation measures were used. The key performance metrics assessed were:

Qualitative
- Visual estimation of jitter and stability
- Map alignment accuracy

Quantitative
- GNSS/INS/UKF variance
- Track deviation from ground truth

Trials were carried out in varied environments with a mixture of open space, dense urban structures, and foliage.

7. FINAL DESIGN

7.1 Architecture

The localisation architecture used by the nUWAy platform is composed of two main sections: the LIDAR pipeline and GNSS/INS odometry fusion engine. The LIDAR and GNSS/INS subsystems operate independently of each other to produce the `[map]` and `[odom]` transforms respectively. These transforms are then combined by the TF tree to produce the overall pose estimate.

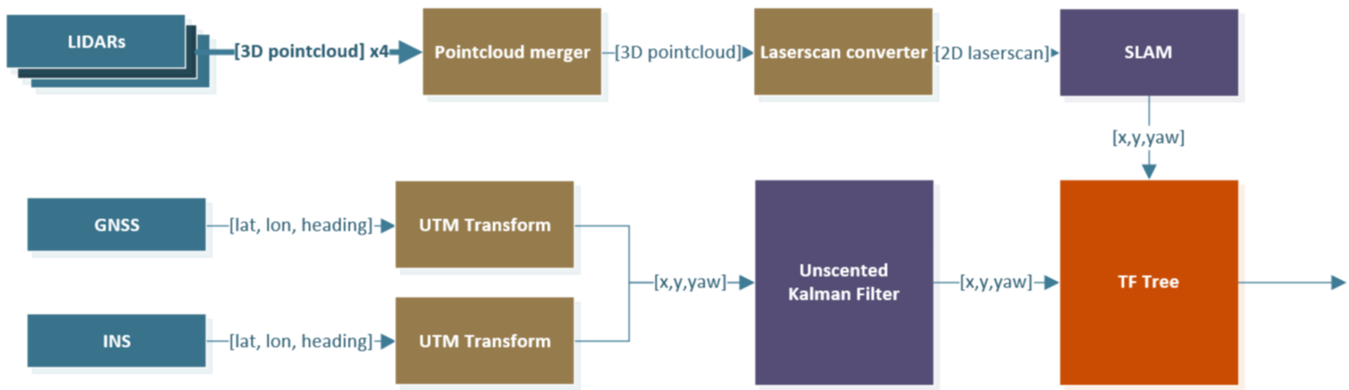


Fig. 2: Logical overview of the nUWAy localisation architecture

While the platform was fitted with an Xsens INS this sensor was not utilised in the final design. Large biases and noise rendered the device unsuitable for providing accurate localisation. Consequently, the final architecture relies on the NovAtel GNSS, SBG INS, and SLAM Toolbox for localisation.

7.2 ROS2

A decision was made to migrate the nUWAy platform from ROS1 to ROS2 as the new release has been significantly redesigned to provide numerous performance and usability improvements. Most notably

ROS2 provides a vastly improved multi-machine experience due to the use of Data Distribution Service (DDS) as a connectivity middleware. The primary advantage of DDS is its discovery system which is, by default, completely distributed such that there is no single point of failure that would prevent parts of the system from communicating with each other. Furthermore, most DDS implementations use zero-copy shared-memory interfaces for inter-process communication when possible, yielding significant performance improvements over the legacy ROS connectivity framework for nodes running on the same machine. Through DDS, ROS2 provides a tangible reliability and performance benefit over ROS1.

Since the performance benefits that DDS brings are only applicable to software running on the same machine, the nUWAy localisation system was architected such that systems utilising large volumes of data, specifically SLAM and the LIDAR pipeline, were all run on the same machine.

7.3 Transform tree

The ROS ecosystem composes robot poses using a tree of reference frames known as the TF tree. The TF tree describes the reference frames as a geometric transform from a parent frame to a child frame. The nUWAy system uses three primary reference frames in its TF tree.

The `[base_link]` frame is centred on the vehicle's centre of mass and the origin of which is interpreted thusly as the position of the vehicle. This frame is described relative to the `[odom]` frame by the `[odom] -> [base_link]` transform which gives the vehicle pose relative to the origin of the `[odom]` frame located at a fixed datum point. This makes the `[odom]` frame an absolute reference frame as a given pose will always correspond to a specific physical location, so long as the datum point is not altered.

The tree's root frame is the `[map]` frame. The `[map]` to `[odom]` transform is published by SLAM Toolbox and describes the offset required to align the odometry frame to the SLAM map. The platform's position relative to the map is thus given by the chained application of the `[map] -> [odom]` and `[odom] -> [base_link]` transforms.

7.4 LIDAR Pipeline

The LIDAR pipeline consists of the LIDAR device drivers, point cloud assembler, laser scan converter, and SLAM node. There are 4 LIDARs used for localisation on the nUWAy platform consisting of 2 wide field of view Velodyne's and 2 long range Ibeo Lux LIDARs each of which has a ROS driver node that outputs raw point clouds.

The SLAM implementation used expects a single LIDAR data stream, requiring that the individual point clouds be merged. For this purpose, the `pointcloud2_assembler` node was developed. This node subscribes to the individual point clouds topics and buffers the latest point cloud received from each sensor. It publishes, a fixed frequency, a merged point cloud that is the union of the latest cloud received from each sensor.

The merged point clouds must then be flattened into a 2D laser scan before they can be consumed by the SLAM node. This was achieved using the ROS `pointcloud_to_laserscan_node` [30]. The flattening process can be configured with an optional minimum cut-off height. As visible in Figure 3 the raw LIDAR data picks up considerable ground return with has a detrimental effect on SLAM performance. Specifying a cut-off level above the ground height serves to filter out the ground return improving SLAM performance. Furthermore, dynamic obstacles within the environment such as vehicles, bicycles, and pedestrians can degrade SLAM performance as they decrease the confidence of the scan matcher when they move. Through experimental testing a cut-off height of 2 meters was found to suitably exclude most dynamic obstacles and ground return.

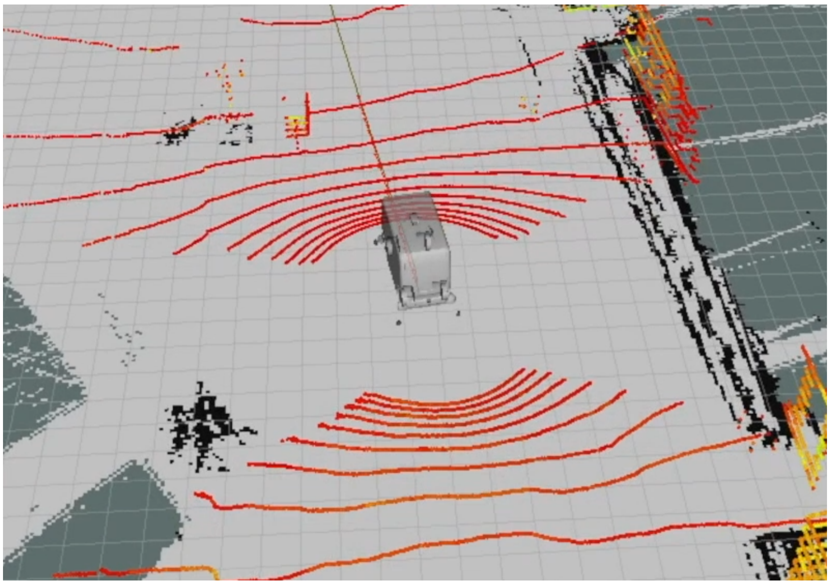


Fig. 3: Visualisation of raw LIDAR data demonstrating ground return.

The SLAM processing of LIDAR data is performed by SLAM Toolbox. This node has been configured to take in odometry data, LIDAR scans, and a pre-generated map to localise the vehicle.

7.5 RTK Correction Feed

GNSS performance was enhanced using a live RTK correction feed. This feed was delivered via the AUSCORS NTRIP broadcaster which provides RTCM data streams via the internet. The data feed was sourced from the Curtin University base station, located around 7.5 km from the UWA campus. Efforts are currently underway to establish a base station at the UWA campus, however this project has yet to be completed and the system is not yet operational. To access the RTK feed, the vehicle requires a consistent internet connection, which is currently provided via a Sierra Airlink 4G modem. This link is currently serviced by the Optus 4G network.

7.6 UTM Transform

During the design process a decision had to be reached about the primary reference frame used by the localisation system. The GNSS and INS systems used on the nUWAy platform both natively report in the Earth centric World Geodetic System 1984 (WGS84) coordinate system while 'slam-toolbox' uses a 2D cartesian system and 'robot_localisation' operates in either 2D or 3D cartesian mode. To remain consistent with the ROS conventions outlined in REP105 [31] a 2D cartesian coordinate system was chosen. This coordinate system is centred around a static WGS84 datum point and is aligned with its x-axis facing east and y-axis facing north. To use WGS84 measurements with this reference frame the measurements must be transformed using a Universal Transverse Mercator (UTM) transform to project coordinates into the local frame.

The UTM transform divides the Earth into 60 UTM zones, each spanning 6° of longitude. Every geographical point measured in latitude ϕ and longitude λ is mapped to a zone and projected using a

Transverse Mercator projection to produce an easting and northing relative to the origin of the zone. The origin point of the projection is located at intersection of the equator and the zone's central meridian. UTM coordinates are related to the local frame using a static reference datum.

$$(x, y)_{odom} = \text{UTM}(\phi, \lambda) - \text{UTM}(\phi_{datum}, \lambda_{datum})$$

The UTM transform was implemented in a custom node written in C++.The node receives INS and GNSS data which is transformed from its native geocentric format into cartesian coordinates in the odometry frame.

7.7 Odometry Fusion

An Unscented Kalman Filter was chosen to fuse INS and GNSS data. The 'robot_localization' package was utilised to implement sensor fusion through its 'ukf_localization_node' which provides a ROS2 compatible UKF implementation. The filter consumes the transformed odometry messages from the UTM transform node and produces a pose estimate in the `[odom]` frame.

7.8 Initial pose estimation

Since the system generates the SLAM map with reference to the absolutely referenced GNSS/INS odometry data, the map can generally be assumed to be aligned, within some degree of error, to the odometry frame. Thus, when attempting to localise the platform within an existing map, the odometry pose may be considered as a good initial estimate for the robot's pose within the map frame. The system has therefore been designed to initialise the odometry system prior to starting SLAM, allowing SLAM Toolbox to use the odometry pose for initialisation.

8. Results and Analysis

8.1 Heading determination

Two sources of absolute heading reference were evaluated for the design. The first, magnetic heading uses magnetometers to measure the Earth's magnetic field providing orientation relative to magnetic north. The other source of heading information is GNSS heading which takes readings from two GNSS antennas mounted at known positions on the platform. Trigonometric principles can then be used to derive heading from the two readings.

Initial plans were to fuse both GNSS and magnetic heading using a UKF, however experimental testing involving measurements taken with the vehicle located at a static rest position within the UWA campus revealed that magnetic heading was not suitable for use in dense urban environments. Figure 4 demonstrates that magnetic heading could drift at a rate of up to 2° per minute while GNSS heading remained consistent with deviation of less than 0.2° over a four minute period. Further attempts at recreating the experiment resulted in drastically different magnetic headings as shown in Table II indicating that the magnetometer readings were highly unstable. These results are evidence of the impact of magnetic interference on the platform. As a consequence, it was decided that GNSS heading would be used as the sole source heading reference used on the platform.

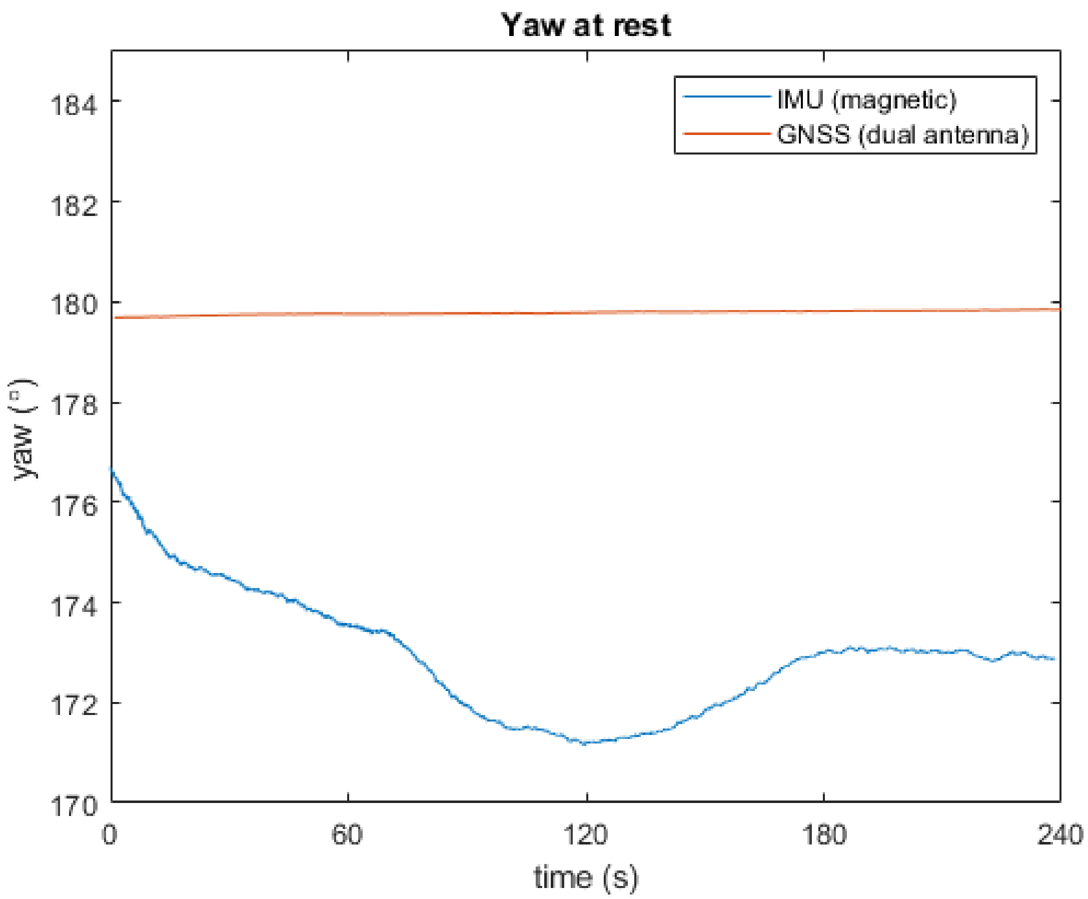


Fig. 4: Comparison between Magnetic and GNSS derived heading

TABLE II: Average magnetic heading reading from repeated observations

Trial	Average Heading (°)
1	173
2	240
3	107
4	131

8.2 GNSS Evaluation

During testing the performance of dual and single antenna GNSS units was compared. The Novatel OEM628 and raw GNSS output of the SBG Eclipse-D were used to simultaneously obtain single and dual antenna GNSS reading respectively. Both units are high performance GNSS receivers with similar specification and both units had a reliable RTK correction feed for the duration of the testing. The test was carried out on the UWA campus in an area that transitioned between open space and dense urban areas.

The track presented in Figure 5 shows readings taken from the GNSS receivers and the ground truth path that was driven. Throughout the test the dual antenna GNSS demonstrated significantly better performance than the single antenna unit. Both units were able to accurately track the vehicle for the first 40 m when travelling through an open, unobstructed area, however the accuracy of the single antenna GNSS rapidly degrades as the platform approaches buildings. The dual antenna unit also exhibits performance degradation, however it is much less severe than that exhibited by the single antenna unit. These observations are reinforced by Figure 6 as initially both units have comparable

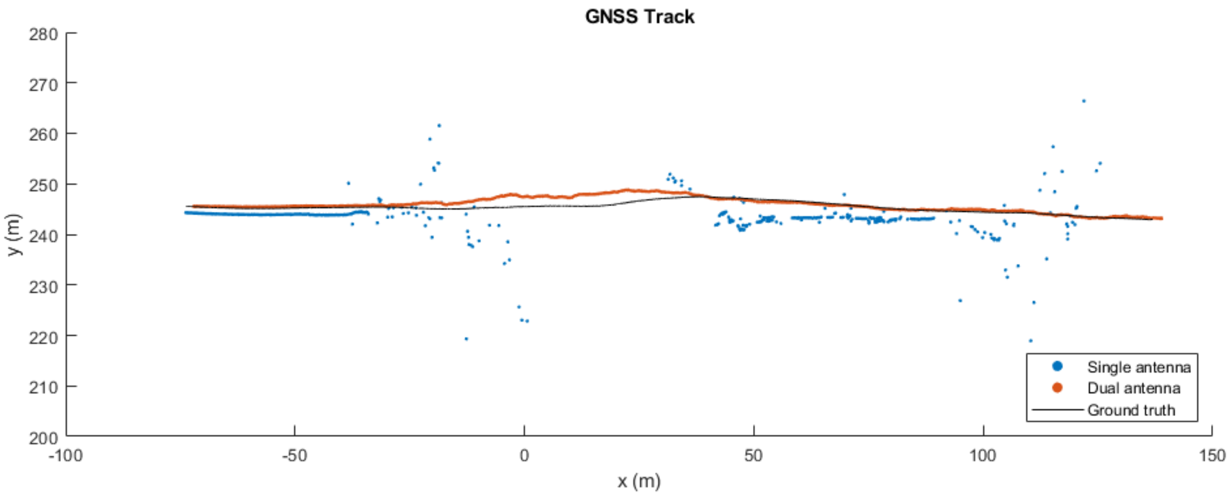


Fig. 5: Data logged from dual and single antenna GNSS units

covariances of approximately 0.0004 which rapidly increases as the vehicle progresses. Both units show similar covariance trends as the vehicle moves past buildings and trees, however in GNSS challenged areas the single antenna unit is consistently less accurate by over an order of magnitude.

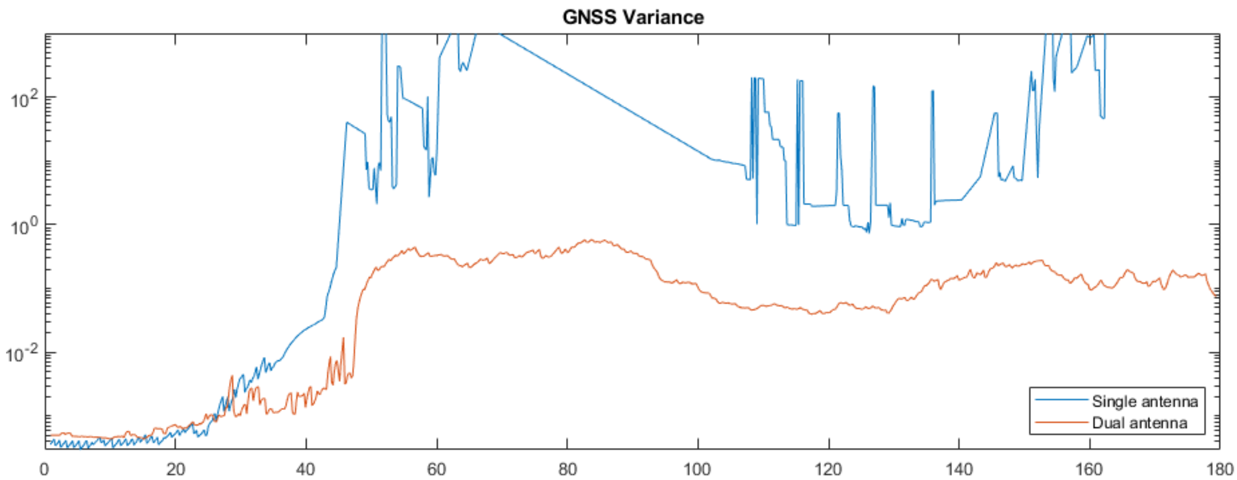


Fig. 6: GNSS covariance measure in an urban environment

It is clear from the results that dual antenna units demonstrate superior error rejection and provide better accuracy than single antenna units. Coupled with the ability of dual antenna GNSS systems to calculate vehicle heading while stationary it is clear that a dual antenna unit should be preferred for use in urban applications.

8.3 Sensor Fusion

Sensor fusion was performed both by the SBG INS which performed onboard fusion of the integrated GNSS and inertial sensors, and by the 'robot_localization' UKF filter. The internal filter of the INS was found to be highly performant and accurately tracked the driven path in both regions with and without GNSS good coverage. Evidenced in Figure 7, the GNSS tracks are accurate in the open carpark area but diverge from the true path in the narrow corridor between two buildings.

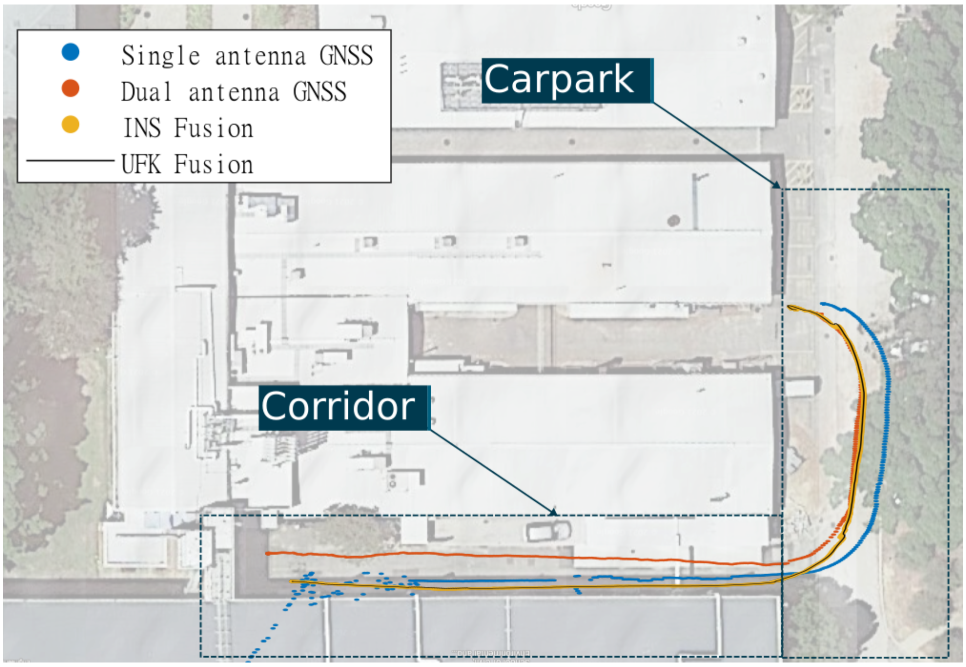
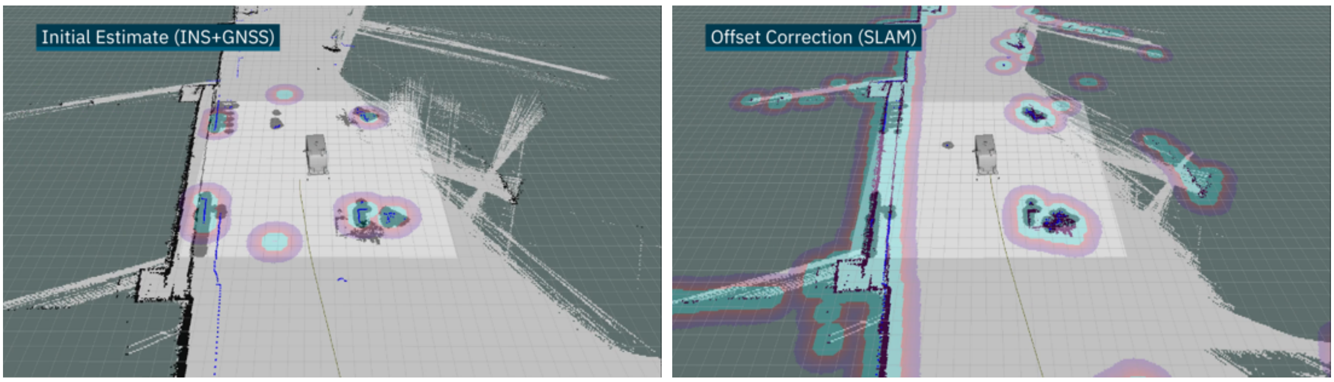


Fig. 7: Odometry fusion trial in open and obstructed spaces

The SBG INS rendered the UKF largely redundant, however the node was kept as it provides additional redundancy in the event that the INS is rendered inoperative. Furthermore, keeping the node will allow for additional odometry sources to be easily integrated into the system in the future.

8.4 SLAM Localisation Performance

The SLAM localisation process was evaluated based on qualitative measures and coarse measurements. During testing the vehicle was frequently restarted in order to test various software configurations. During 20 observed restarts the vehicle would reliably localise to within 1 m of the correct map position in every instance, as demonstrated in Figure 8. During testing it was found that if the initial alignment was marginally offset from the map, then the SLAM algorithm would generally correct the pose after several seconds.



(a) Initial GNSS pose estimate (b) Pose after SLAM initialisation

Fig. 8: Demonstration of the SLAM initialisation process

The SLAM system was found to accurately track the vehicle in areas with several building in close proximity however, it was found that SLAM localisation could drift in ‘noisy’ areas with few distinct features or low quality LIDAR mapping. Areas of the campus with significant foliage were found to be most prone to inducing error. Figure 9 provides one such example whereupon travelling through an avenue lined by trees and shrubbery a visible misalignment to occurred. Further work will need to be completed to ensure the system is robust against such occurrences.

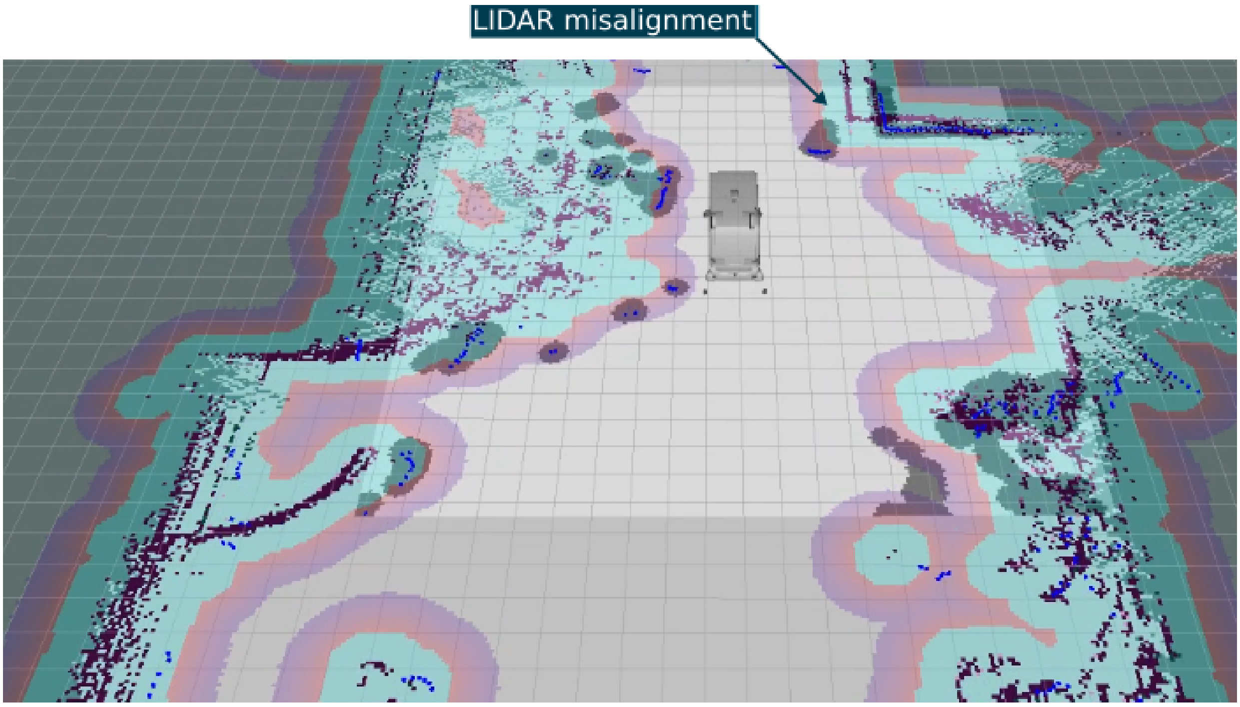


Fig. 9: Demonstration of map misalignment a foliage dense area

8.5 General Performance

In the trials undertaken the nUWAy shuttle was driven through the urban surrounds of the UWA campus. As expected, best results were achieved in locations with significant, single level structures that facilitated accurate SLAM localisation without significantly degrading GNSS coverage. Larger multi-level construction had a noticeable impact upon GNSS localisation performance, however these effects were largely compensated for by the inertial sensors of the INS. It is expected that the INS would accumulate greater error with longer, more significant GNSS disruptions, however long-term disruptions were unable to be tested within the timeframe of the project.

Ultimately the SLAM system presented the most challenges, as it had difficulty maintaining accurate tracking in areas with poor quality mapping. It is therefore recommended that a new map of the campus be generated before the service commences regular operations.

8.6 Limitations

In order for the UTM transform to correctly map WGS84 coordinates to the robot’s local reference frame, all WGS84 referenced measurements must lie within the same UTM zone as the reference datum. Given the limited operating area of the nUWAy platform this limitation is not likely to impact the platform during normal operations, however it may present an issue if services are expanded into other geographical regions. Overcoming this limitation would require modification of the localisation system to support multiple maps for different UTM zones and a mechanism for switching between maps as the platform transits between zones.

9. Future Work

The following recommendations are made based on an evaluation of the outcomes of the project.

9.1 Datalink Redundancy

The need for a reliable stream of real time RTK corrections from a remote base station to facilitate high accuracy GNSS introduces a dependency having a reliable datalink to the base station. At present this is datalink is provided over the internet via a 4G data modem integrated into the nUWAy platform. Given that prolonged disruption to the datalink severely degrades localisation performance, it would be worthwhile to investigate alternative communications technologies that could be used to provide a backup datalink. Promising technologies for evaluation include UHF datalink, satellite based GNSS augmentation, and LoRaWAN.

UHF datalinks provide reliable, mid-range, low bandwidth communications and are commonly employed in commercial applications. The nUWAy shuttle bus is currently equipped with a SATEL UHF modem that operates in the 400 MHz band in the 403-473 MHz frequency range and is capable of a data rate of up to 28.8 kbps [32]. This data rate would be sufficient to sustain an RTCM RTK correction stream, however ACMA requires a Land Mobile license be obtained in order to operate radio equipment in the 400 MHz band [33]. Additionally, a UHF base station would be required to broadcast the requisite RTCM stream and this base station would also require a license to operate. Land Mobile Licenses are also subject to geographic restrictions which would limit the regions in which a UHF dependant platform could legally operate in.

Satellite Based Augmentation System (SBAS) technologies are employed around the world to provide long range GNSS augmentation. These systems are typically less accurate than ground based alternative but have the advantage of covering large geographical areas. At the time of writing a government led project is in the works that aims to provide nationwide SBAS coverage by 2022 yielding 10 cm positioning accuracy throughout Australia and 3-5 cm accuracy in areas with mobile coverage [34]. Being satellite based, SBAS would not require the operation of a ground base station or any additional licensing. Since SBAS operates within the same frequency range as GNSS itself it is liable to face similar challenges and drawbacks. Another consideration is that, unlike the other proposed technologies, SBAS is unidirectional single-purpose datalink which limits its use solely to GNSS augmentation whereas alternative technologies may be co-opted for general purpose telemetry.

LoRaWAN is a long range radio protocol that provides low bandwidth data connectivity using license free radio bands. This technology is relatively low cost but is more prone to being disrupted by interfering signals than other alternative technologies.

9.2 Wheel Odometry

The nUWAy shuttle is equipped with wheel position encoders that can be used to provide odometry information, however they are not currently utilised as there is no current means by which the encoders can be read by the bus computers. The encoders are currently connected directly to the vehicle's traction controller and would need to be intercepted to be used by the localisation system.

9.3 GNSS Modelling

While simulation facilities were available to aid in the testing and evaluation of the proposed design, they were found to be of limited use due to the relatively simple sensor model employed by the simulator. Of significant note was the GNSS model which was incapable of accurately emulating the complex effects that urban environments have on GNSS signals. An accurate GNSS signal model capable of simulating the impact of sky occlusion and multipath effects on GNSS measurements would greatly accelerate the testing and design of future GNSS based localisation systems.

9.4 SLAM Performance Study

During experimentation is became apparent that environment conditions, such as heavy precipitation could have a detrimental effect on SLAM localisation performance. The potential for such performance degradation has serious safety implications and consequently it is suggested that a rigorous study be carried out into the impact of adverse environmental conditions on SLAM performance. Significant factors for consideration include fog, precipitation, and dust. A rigorous study would help to ensure confidence in the safety of the platform.

10. Conclusion

This project succeeded in developing a localisation system that behaved well in practical tests, being able to localise quickly and accurately in a complex urban environment. Testing demonstrated good resilience against momentary GNSS disruptions, however, it was found that the current SLAM system has difficulty maintaining accurate localisation in areas with large areas of foliage. Ultimately the current state of the system allows for basic autonomy in well-conditioned areas, but further work is required improve reliability in diverse environments and weather conditions.

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