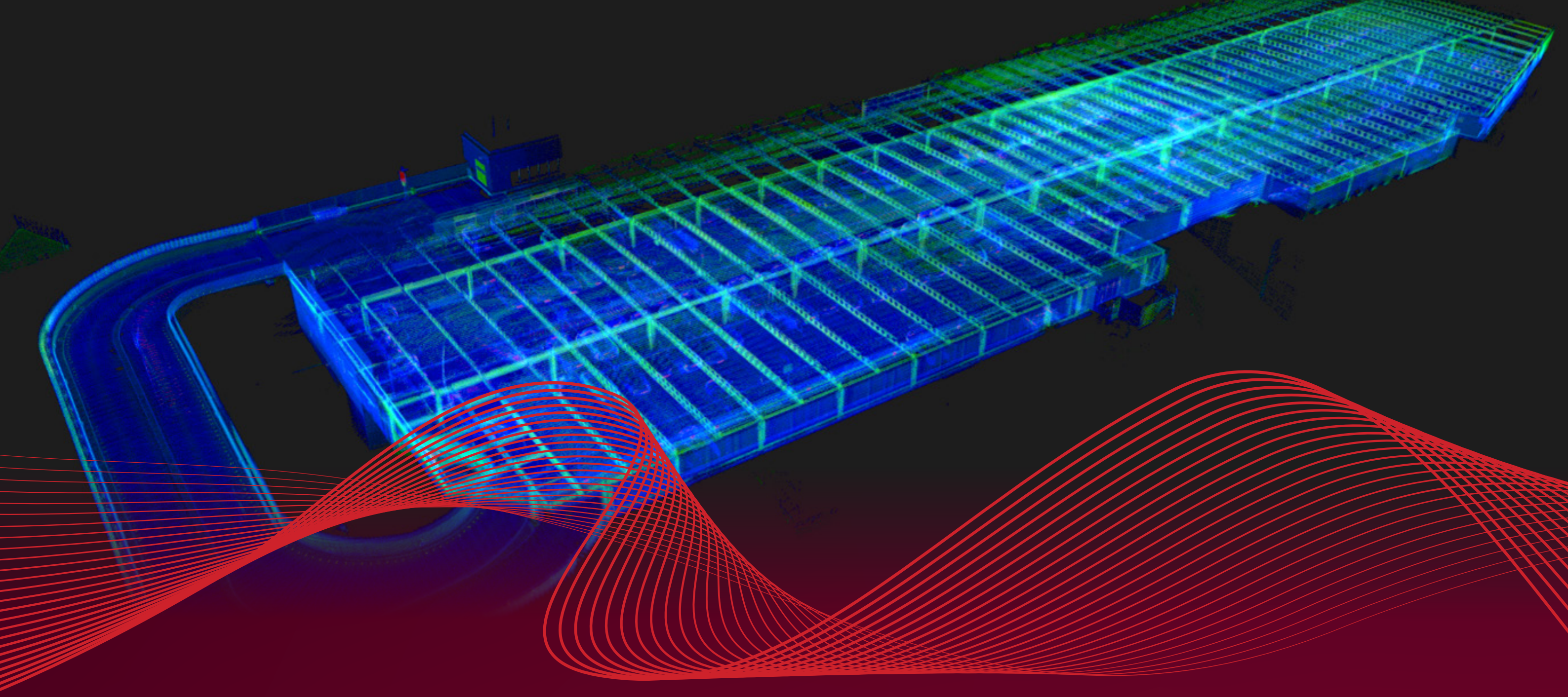


TECHNICAL ARTICLE

LiDAR INERTIAL ODOMETRY (LIO)

Combat the effects of position drift in urban canyons using LiDAR

OxTS' new LiDAR odometry solution uses an IMU-GNSS tightly coupled INS system to deliver innovative, high-precision and high reliability navigation data in any environment. OxTS LIO significantly reduces drift and improves performance in GNSS-denied or GNSS-harsh environments such as urban canyons.

OxTS LIO ensures position drift is kept under control. The feature can be used in any application and is useful for:

- Asset Management
- Building Information Modelling (BIM)
- Coastal Monitoring
- HD Mapping
- Infrastructure Monitoring
- Land Surveying
- Mining
- Road Monitoring

OXTS

About LiDAR technology

LiDAR technology is being increasingly used in many different sectors, notably the Automotive industry and the Survey and Mapping industry. Its high precision and practicality in making a 3D image of the surrounding environment has lent itself to being the go-to technology for development of autonomous driving applications and mobile mapping.

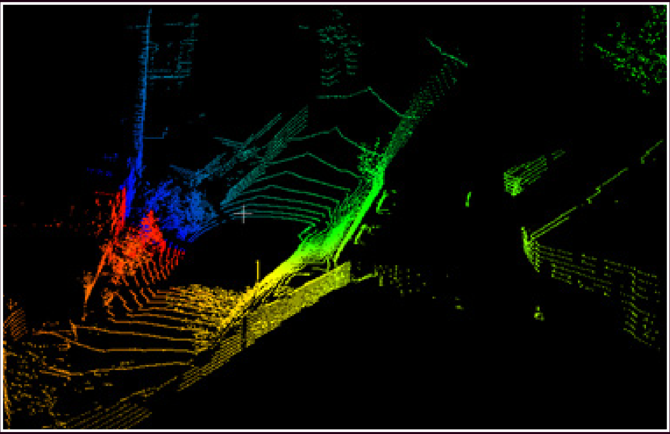
Vehicles equipped with LiDAR can efficiently create maps of the environment or to detect and navigate obstructions.

LiDAR has also proven to be effective at not just detecting objects in the vicinity but also to provide accurate relative position and timing information and therefore velocity information.

By utilising this and feeding the odometry measurements that LiDAR can produce into a navigation system such as an OxTS INS device the navigation data is enhanced and made more robust. This is particularly useful where the other aiding sources of the INS, namely GNSS, are not capable of providing accurate information.

This can happen in many different environments. Anywhere that GNSS struggles or is blocked, such as a multi-storey car park (seen above) or an significantly urbanised area, will strain the INS solution very quickly. Consistent updates from a LiDAR odometry system however can mediate these difficulties.

360° field of view LiDAR sensor


A frame of LiDAR data taken as a vehicle moves across a road

How it works

The typical operation of an automotive-grade LiDAR is to produce a 3D scan of the environment with each revolution of its internal components. Lasers within the devices are split into channels of different elevations (as seen on the here) and these channels are rotated 360 degrees.

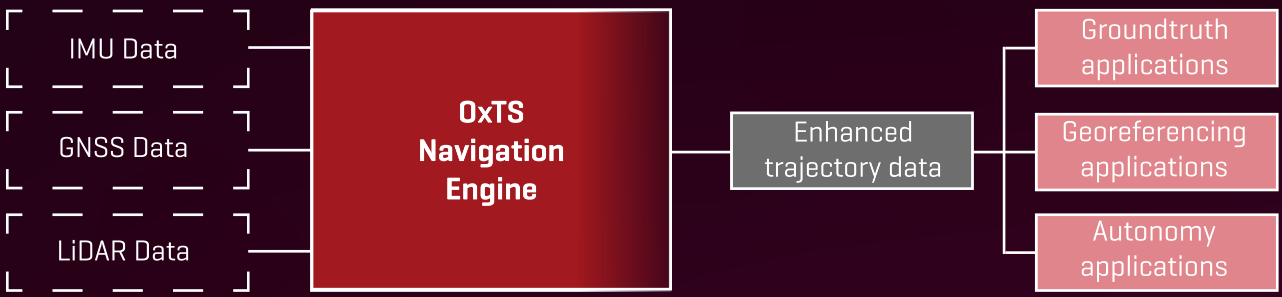
These channels might run at a typical 600RPM (10hz). When the laser pulses that are emitted from the device are reflected by an object and the device measures their corresponding reception time.

What happens next?

From the timing of the reflected pulse a range is calculated. Using the channel elevation, rotation azimuth, and the range, a 3D image is constructed. Each revolution gives a 'frame' of the local environment seen during the time period of one revolution.

Thus, over multiple revolutions a series of frames are produced along the trajectory of the vehicle.

3D pointcloud created using an OxTS INS and LIO.



Each frame then needs to be classified. The scan the LiDAR produced is screened to identify, categorise and quantify geometrical objects with noise being filtered out. Planar objects are identified and quantified as planes. Edges of objects are identified and quantified as lines. A wall for example is categorised as a plane with the measured planarity and location in the frame.

The next step in determining the odometry is to compare subsequent frames. If the same object is viewed in both frames then the difference in its relative position and orientation can be determined.

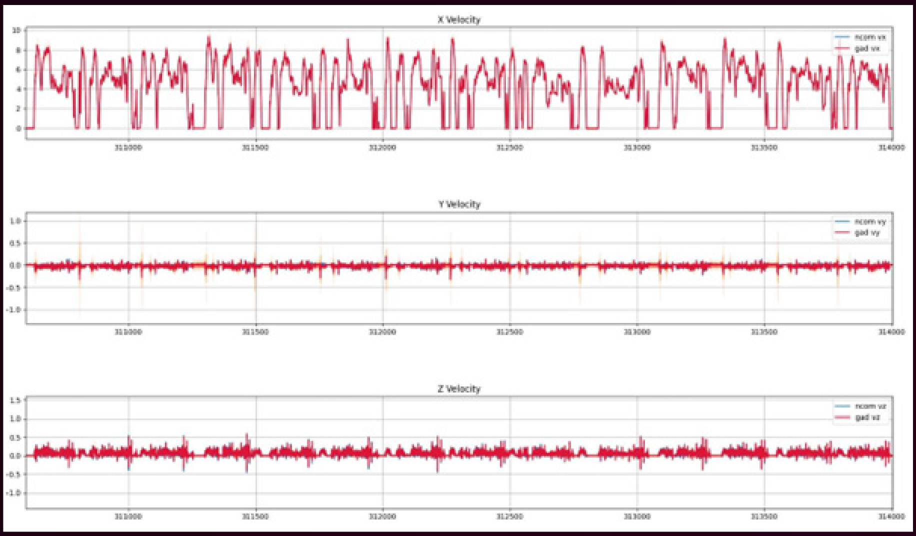
Then, using the timing difference between frames, linear and angular velocities can be calculated. Finally, covariance values must also be accurately calculated. This measure of the uncertainty of the velocity calculation can be estimated by considering the spread of LiDAR points on an identified object.

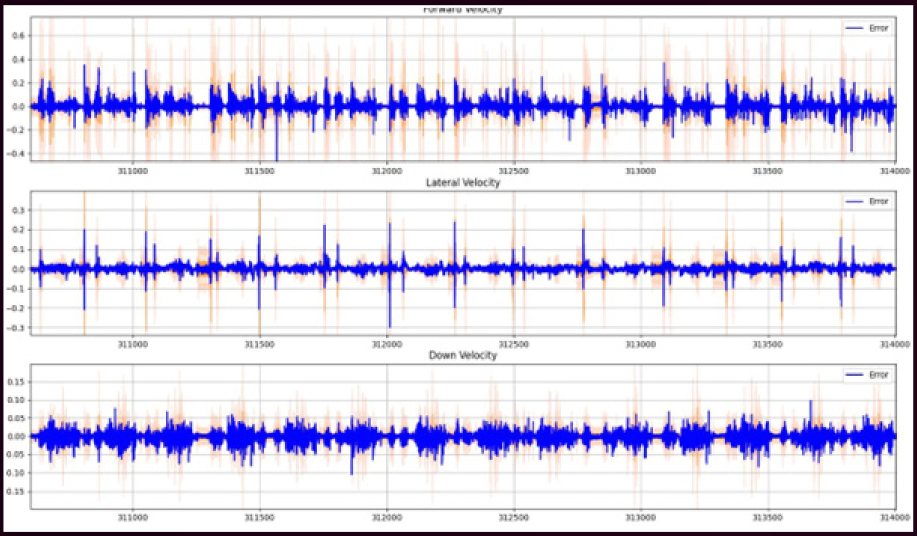
From this a stream of high precision odometry updates with associated covariance values is produced at a high rate (100Hz) that can be fed directly into the Kalman Filter of an OxTS INS device.

Performance evaluation: Oxford

The data was collected in the city of Oxford using an RTK Integer reference dataset. Oxford was chosen as it closely resembles other urban areas. Please note that these values may vary depending on your LiDAR set-up and the environment.

Performance of the LiDAR odometry as a standalone solution can be quantified by comparing its output to a reference. The following graph is of a dataset of multiple laps in the city of Oxford. It is a plot of the velocity output on each axis from LIO (red) and the reference INS (with RTK) in blue. As is seen, there is almost complete overlap:





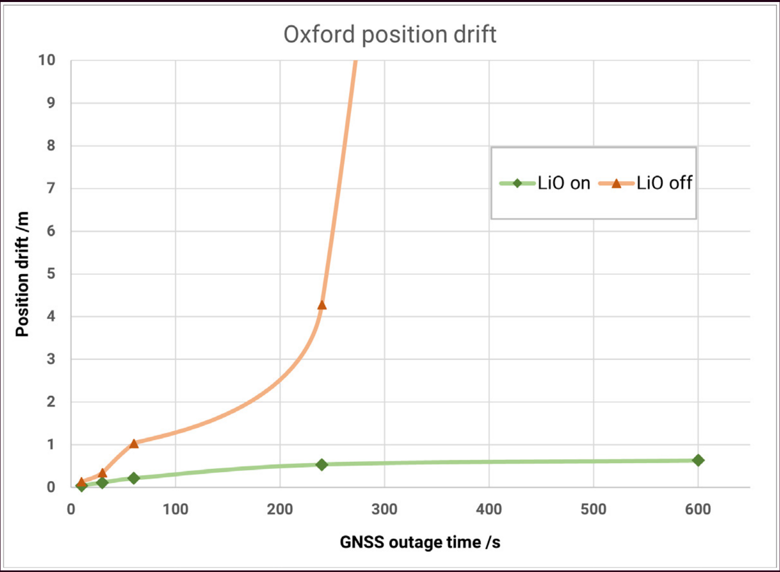
Focusing in on the errors between LIO and the reference, the next plot shows the measurement error for each axis. As can be seen, the errors in lateral and down velocity are very small, consistently below 0.05m/s. forward velocity is generally the most important for vehicular travel and shows similar accuracies.

More importantly we can evaluate the performance of an INS system which uses these velocity measurements as an input. One of the key points of interest for LIO is improving navigation where GNSS is not present.

“The collection is very quick. Once the unit is on, the initialisation and warm up time are minimal and we’re collecting data quickly. We boresight every so often, but our setup is quite static. For mobile mapping this is an extremely cost-effective way of gathering data.”

Results

GNSS outage duration /s	Position /m	Heading /°	Roll /°	Pitch /°	Velocity /ms-1	Altitude /m	3D distance travelled /m	Position percentage error /%
10	0.041	0.015	0.005	0.006	0.008	0.029	40.797	0.1
30	0.112	0.033	0.008	0.01	0.016	0.061	130.656	0.08
60	0.212	0.048	0.012	0.014	0.025	0.106	257.211	0.08

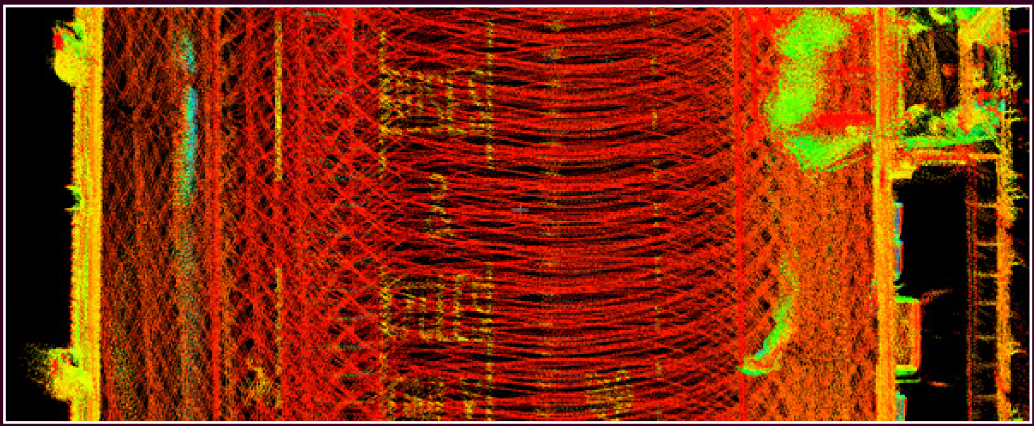


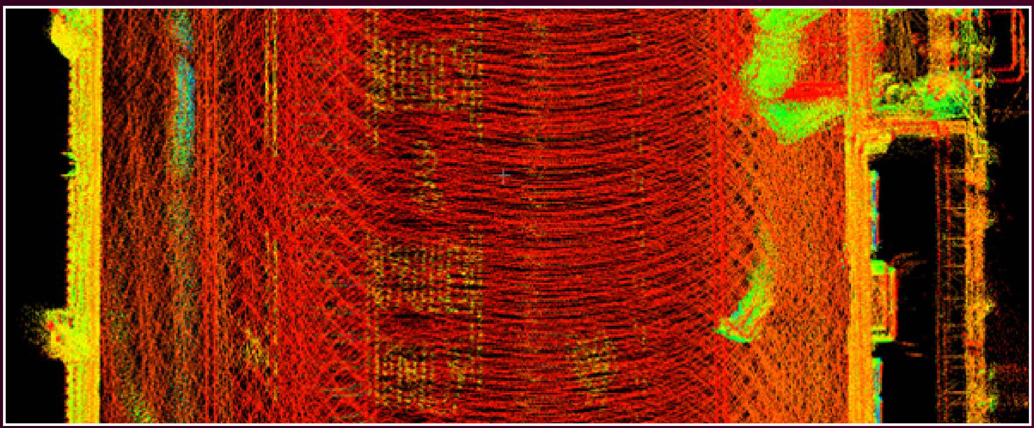
Plotting the position drift over time we can see that LIO alters the projection order of the drift. Whereas IMU only drift is exponential, when LIO is also used the projection is closer to logarithmic (square root):

With GNSS made unavailable, survey repeatability becomes impossible. Without LIO, subsequent laps of the Oxford loop do not overlap by some tens of meters.

With LIO however there is almost complete overlap still. This can be seen in the images below. The first is the overlap of a reference dataset and a dataset with LIO aiding but no GNSS for 30 seconds.

In this birds-eye view of the road you can see the close overlap and make out the text on the road.





However on this second image of the overlap of the reference data, and a dataset without LIO aiding, but 30s of GNSS outage can be seen. As is clear, when LIO is not present drift can quickly reduce pointcloud and trajectory repeatability.

Performance evaluation: London

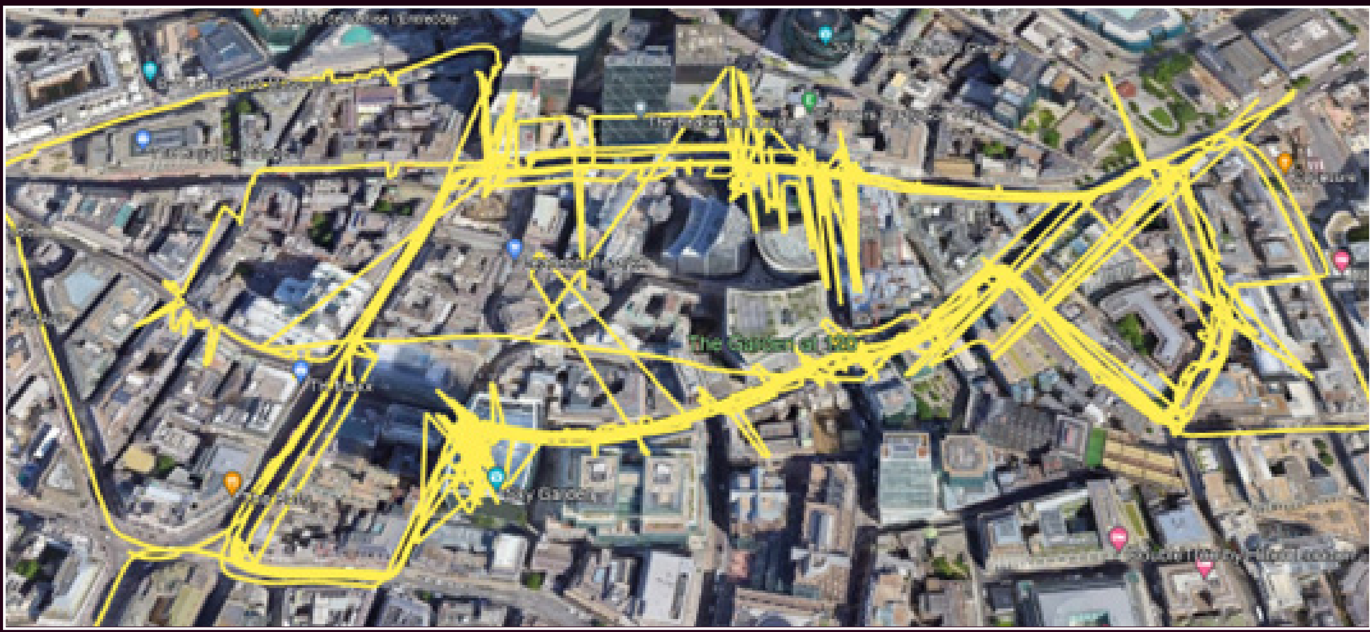
Significant improvements can be made to data taken in challenging GNSS environments. The City of London is the most built-up area of the United Kingdom and features many high-rise buildings that block satellite signals preventing GNSS localisation. On top of this, satellite signals are reflected off the surfaces of the buildings producing extensive 'multi-path' errors. These sparse and often false measurements from the satellites make navigating in this environment one of, if not the, toughest navigation challenges, often more so than zero GNSS locations.

An OxTS RT3000 INS

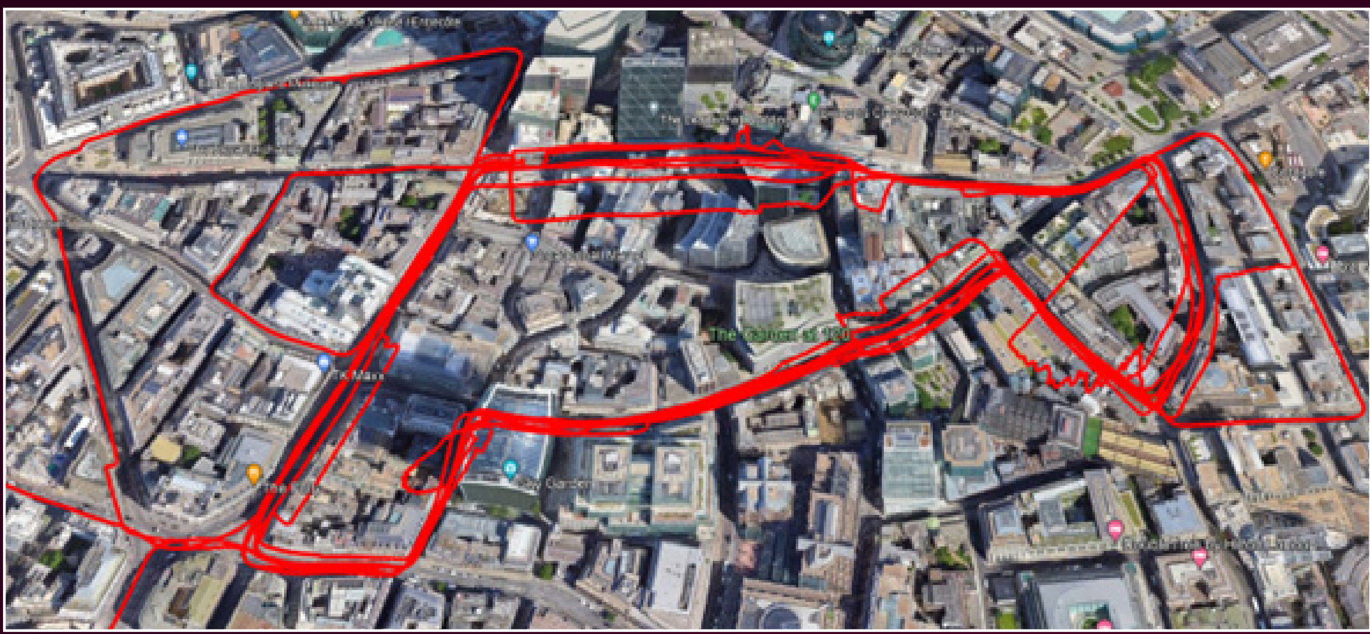
An IMU, such as those used in OxTS INS devices, is often used to maintain a trajectory between accurate GNSS updates. However, when GNSS is challenged this often proves inadequate. IMUs drift quickly away from their true position when they are unaided by position updates and it can be some time before a good update is obtained from the GNSS.

An OxTS xNAV650 INS

The following is a Google Maps satellite view of the raw GNSS data from a driven loop of the city of London. The loop was repeated 8 times (for approximately 1 hour):

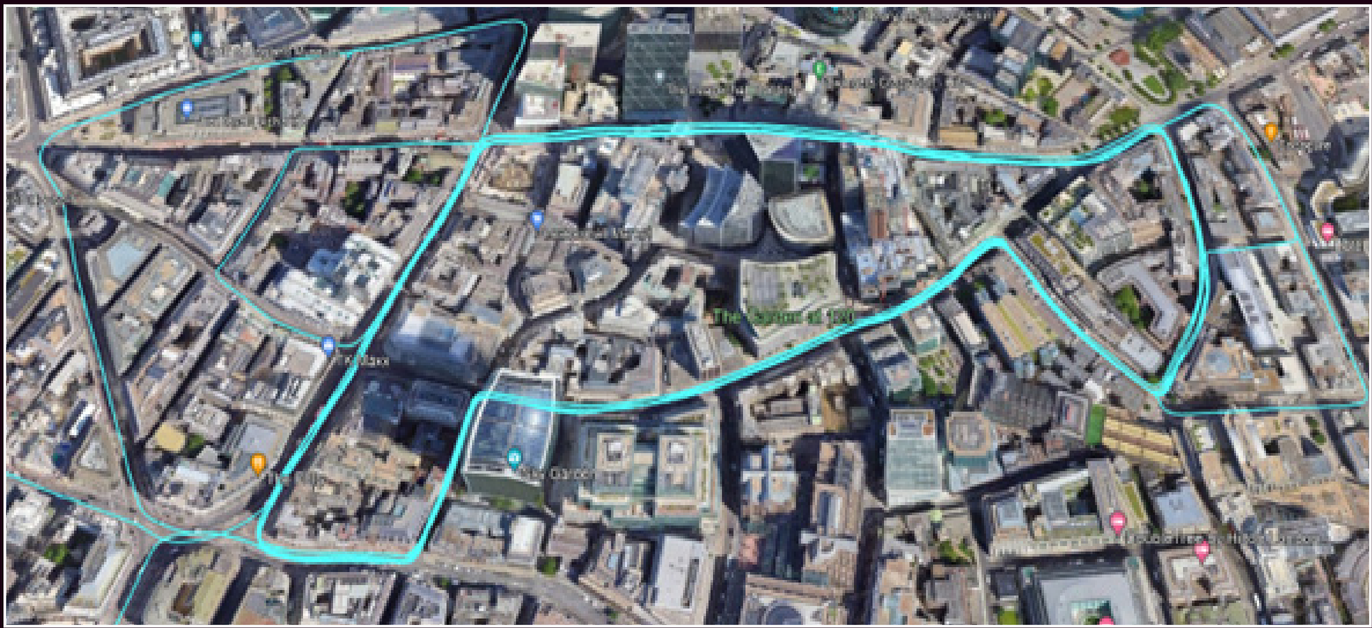


You can see that much of the data is extremely erroneous and not useful for any applications. The next is a view of the same data but processed tightly-coupled with an IMU through a Kalman Filter:



Significant errors remain in the data because the INS goes too long without an accurate GNSS position update to lock it back into the correct position. After long enough, the IMU drift is so large that the GNSS data, as bad as it is, is trusted more and large multi-path errors are accepted as the true position because they are the only updates available for an extended period of time.

LiDAR odometry supplies a constant and accurate stream of velocity measurements to correct the INS trajectory and reject bad updates from GNSS. It can remove any significant shifts in the trajectory and keep the INS on a tight and repeatable path. This way LIO is able to keep the trajectory on the road at all times, with the biggest impact coming from complete GNSS multipath rejection:



Performance evaluation: Multi-storey car park - no GNSS

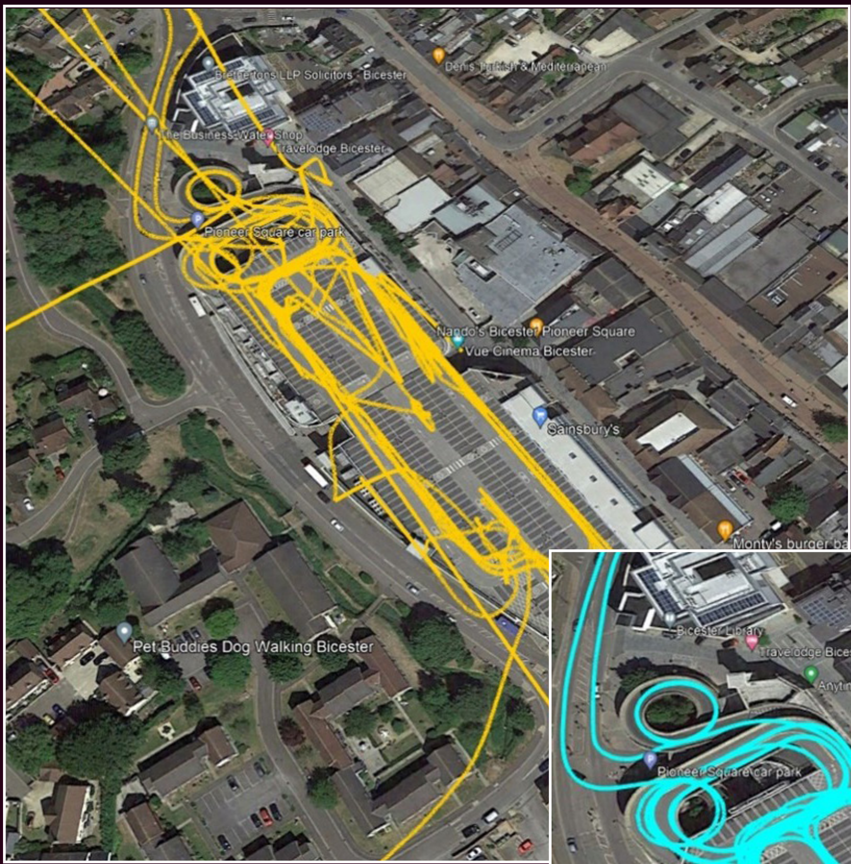
In general, when operating a GNSS-aided INS device for a prolonged period of time without GNSS updates navigation becomes untenable. For example, if a tunnel is part of the route for example then the INS will struggle to maintain a correct position inside the tunnel until it emerges and receives GNSS updates again. Even just a couple of minutes in a GNSS-denied area causes position errors of some tens of meters unless other aiding sources are used such as a wheelspeed odometry update.

As a result navigating a multi-storey car park or something similar as part of a data collection is usually untenable. After 20 minutes the trajectory could have drifted several kilometres (!) from the correct position, LIO reduces this to just meters or less.

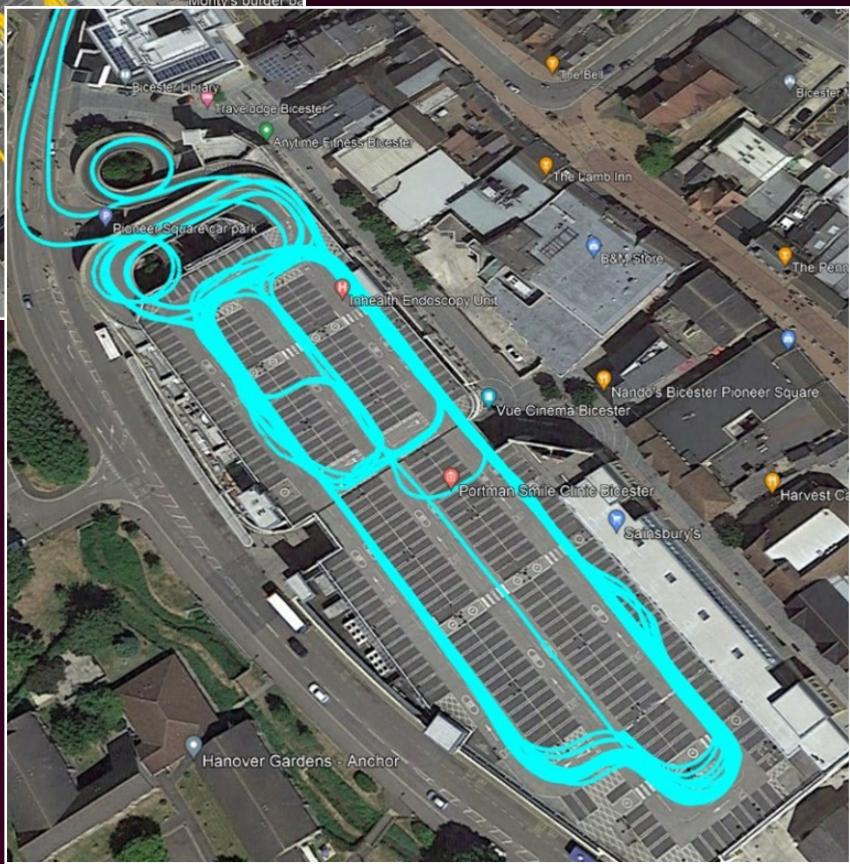
The inside of such a multi-storey car park however gives ideal conditions for OxTS LIO which gives high accuracy updates while GNSS is totally unavailable. Even if the vehicle parks and remains stationary, drift during the GNSS is significantly reduced and curtailed.

See the Specifications section at the end of this document for values of drift performance using LIO.

The following is a view of the trajectory within the car park without LIO aiding. 50 minutes are spent in the car park driving and parking. As can be seen, the INS makes significant errors without any GNSS measurements updating its position. However when LIO is added the INS maintains an accurate position throughout:



Multi-storey carpark
KML trail - without LIO aiding



Multi-storey carpark
KML trail - without LIO aiding

Applications and use cases

Using OxTS LIO with a GNSS-aided INS allows us to get the maximum utility out of both measurement sources. The GNSS allows navigation anywhere in the open world in global frame coordinates that can be compared to any other survey or navigation application. But the LIO adds the ability to transition through poor or GNSS-denied environments. The biggest performance increase can be easily seen in built-up urban environments or in trips with transitions through GNSS-denied or indoor locations.

Since the odometry measurements and statistics depend on the identification and quantification of objects seen frame by frame in LiDAR data, the performance of LIO depends on the geometry of the environment. It is therefore impossible to present specifications for LIO in every use case, but performance is generally repeatable across similar environment types.

Towns and cities are excellent for the algorithms of OxTS LIO to produce consistent and high accuracy updates even with the interference of moving cars and pedestrians. More challenging environments include rural forested areas where trees and hedges do not lend themselves to be classified geometrically, although the ground does.

Tunnels are a unique case in which objects are easily classified but the uniformity of the tunnel frame by frame makes velocity measurement very difficult. Use of a wheelspeed sensor is ideal for tunnel applications.

Survey applications are easily adapted to making use of OxTS LIO. Surveyors using LiDAR to georeference pointclouds can use the same data to improve the navigation data and produce their 3D maps. The improvement in consistency that LIO gives removes jumps in the data that could otherwise be seen in the pointcloud resulting in refined clarity and removal of double-vision errors.

Ground-truthing applications such as using an INS as a reference unit in autonomous driving testing can significantly benefit from the use of LiDAR odometry. LIO opens up more real-world driving scenarios to be accurately tested, whether it is maintaining lane-level trajectory in a built-up city or visiting a multi-storey car park for a prolonged time.

Requirements

To utilise OxTS LIO an automotive-grade LiDAR is required that is compatible with OxTS Georeferencer. The following list is currently implemented in OxTS LIO:

Hesai

XT16, XT32, XT32M2X, 40M, 40P, 40, 64, 128, QT

Velodyne

VLP16, VLS128

Ouster

OS0-32, OS0-64, OS0-128

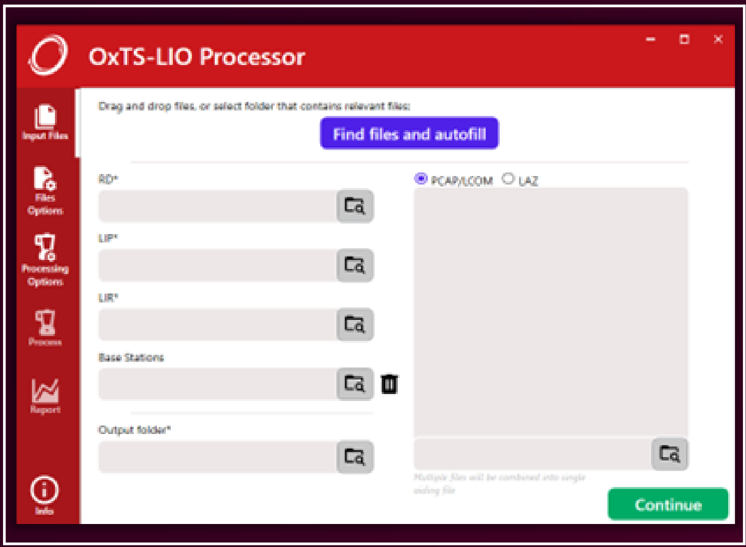
The LiDAR should be mounted rigidly on the body of the car and with respect to the OxTS INS device. The relative orientation and displacement of the LiDAR to the INS must be known precisely. To obtain precise values it is recommended to use a machined mount and the Boresight Calibration procedure of OxTS Georeferencer.

This is very important for getting accurate updates out of the LiDAR odometry. It is recommended that the LiDAR is mounted horizontally level on the top of the vehicle to give it an ideal 360° view.

Example set-up with an INS in the boot of athe car, a Hesai XT32 for LiDAR Odometry and a Z&F Profiler 9020 for mapping

Time synchronisation must be made between the LiDAR and the INS. This can be done either via PPS or PTP. Visit our Support site for manuals and work instructions.

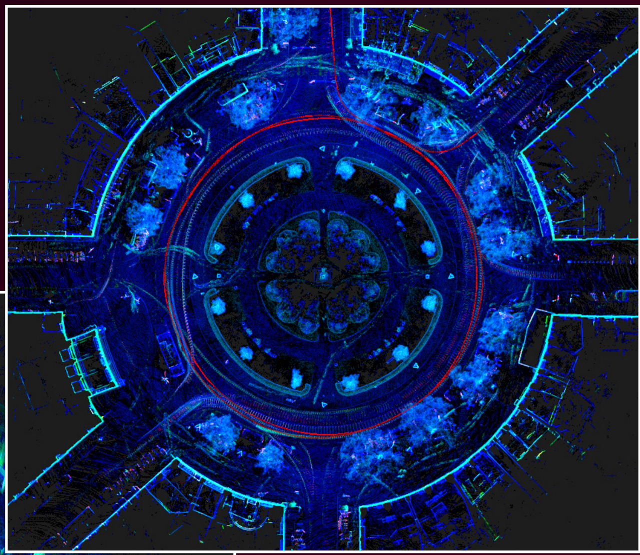
With the setup complete and calibrated the data simply needs to be recorded. All that is required to make use of LiDAR odometry updates is to record the LiDAR data in a standard .pcap format. This PCAP file is analysed by the OxTS LIO algorithm and then transformed into an OxTS 'Generic Aiding' file that is added to the INS processing. Currently OxTS LIO is post-process only.

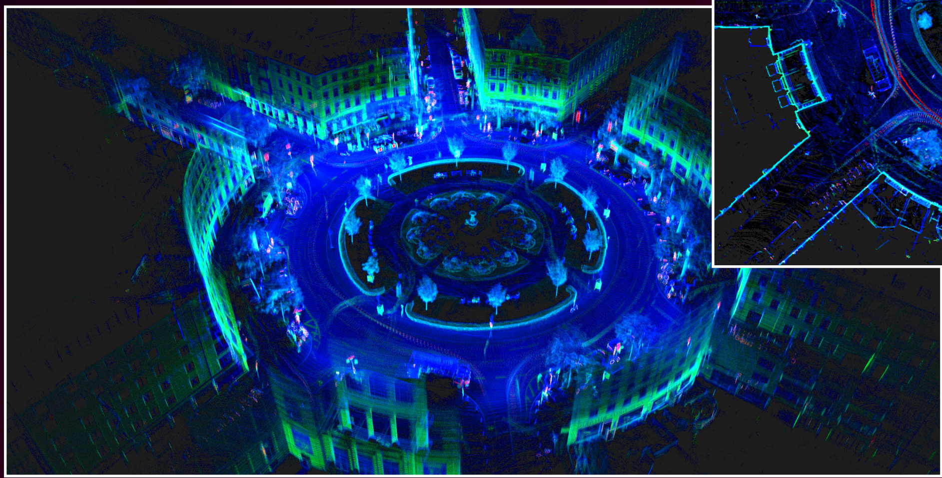


OxTS have also a developed a Graphical User Interface to make configuring the data processing as simple as possible. Files are dropped into the GUI to be processed. The GUI also gives a full diagnostic report of the performance of the LiDAR odometry for that data processing.

Munich data collection

The LiDAR data here was collected in Munich, Germany using an OxTS INS and Hesai XT32 LiDAR. The data was processed using OxTS Georeferencer with the LIO feature enabled. The set-up was boresighted using the OxTS boresight calibration tool.





Specifications

We are able to quote the following specification values that have been obtained statistically using a Hesai XT32 LiDAR device and an OxTS RT3000 v4 INS. Data has been collected in the city of Oxford for these values and closely resembles other urban datasets which can show higher or lower performance values.

Measurement	GNSS Outage [s]	RMSE
Position 2D	60	0.218 m
Heading	60	0.050°
Roll/Pitch	60	0.020°
Velocity 3D	60	0.037 m/s
Altitude	60	0.128 m

Odometry accuracy = 0.03 - 0.05 m/s
Measurement rate = 5 - 20 Hz

OXTS