# Novel Environmental Features for Robust Multisensor Navigation

Debbie Walter, Paul D. Groves, *University College London, UK*;
Bob Mason, Joe Harrison, Joe Woodward, Paul Wright, *Terrafix Ltd., UK*

**Biography**

Debbie Walter is a PhD student at University College London (UCL) in the Engineering Faculty's Space Geodesy and Navigation Laboratory (SGNL). She is interested in multi-sensor integration and robust navigation and navigation techniques not reliant on GNSS. She has a MSci from Imperial College London in physics and has worked as an IT software testing manager.

Dr Paul Groves is a Lecturer (academic faculty member) at UCL, where he leads a program of research into robust positioning and navigation and is a member of SGNL. He joined in 2009, after 12 years of navigation systems research at DERA and QinetiQ. He is interested in all aspects of navigation and positioning, including multi-sensor integrated navigation, improving GNSS performance under challenging reception conditions, and novel positioning techniques. He is an author of more than 50 technical publications, including the book Principles of GNSS, Inertial and Multi-Sensor Integrated Navigation Systems, now in its second edition. He is a Fellow of the Royal Institute of Navigation and holds a bachelor's degree and doctorate in physics from the University of Oxford. (p.groves@ucl.ac.uk)

Dr Bob Mason is Technical Director of Terrafix Limited; integrators and designers of navigation and communications systems. A physics graduate from Imperial College London, he obtained his PhD in communications and neuroscience from Keele University in 1981 and was involved in design of complex systems at Marconi Space and Defence Systems before joining Terrafix. He is a chartered scientist and physicist and a member of the Institute of Physics. His research interests include novel navigation techniques, software defined radio (SDR) and cognitive systems.

Joe Harrison is principal radio frequency (RF) design engineer at Terrafix Ltd. He has been with Terrafix for twenty eight years and has worked on a variety of design and research projects including mobile network radios, GSM modems and radio modems. Before working for Terrafix Ltd he worked for Marconi Space and Defence and Marconi Secure Radio Systems working on a variety of electronic warfare (EW) and electronic countermeasures (ECM) projects.

Joseph Woodward is software design engineer at Terrafix Ltd. He has been with Terrafix for five years and has worked on a variety of design and research projects ranging from low-level embedded software and DSP algorithms through to high-level database and website design. Before working for Terrafix Ltd he worked for Icera Ltd (acquired nVidia Ltd) on their software defined radios (SDR) for cellular networks as part of the Silicon Design Team, which was responsible for world-leading SDR solutions using novel processor architecture, full custom silicon design and layout and industry-leading software tools.

Dr Paul Wright is a development engineer with Terrafix Ltd. He has degrees in physics and in electronics. Prior to working at Terrafix, he has many years experience designing and testing large reflector antennas for radar and satcomms systems. He moved to development in mobile data and navigation systems after work with satellite internet access systems and network management software. He is a chartered engineer, and member of the Institution of Engineering & Technology, and of the Institute of Physics.

**Abstract**

A feasibility study was undertaken to identify a set of novel environmental features that could be used for navigation in the temporary absence of GNSS or degradation of the signal. By measuring these features during times of GNSS availability a map can be produced. This can be referred to during times of limited reception. Therefore a 'measurable' can be defined as a feature either man-made or natural that is spatially distinct and has limited temporal variation.

A literature study was conducted to generate a list of possible environmental features, for which each candidate was assessed for their viability. The features were ranked according to five criteria: temporal variation, conformity to the scenario, ambiguity, precision and coverage. The outcome of the viability study was used to determine which features would be experimentally tested. Magnetic anomalies, road texture and a dozen other environmental features were found to be worth investigation. Features which were discounted include wind speed and pulsars.

The first experiment was carried out on foot in Central London around a closed loop circuit walked three times. An Inertial Measurement Unit (IMU), comprising

accelerometer and gyro triads, together with a barometer, three-axis magnetometer and GNSS receiver were used. Also a camcorder recorded from the point of view of a pedestrian, enabling visual and audio features of the environment to be assessed.

Magnetic anomalies were found to be a promising source of position information. Peaks in the magnetometer data were observed on all rounds at approximately the same positions. Also similarities were seen in the temperature profiles after correcting for the temporal variation of the background temperature. Another potential source of position information was found to be text-based signs.

Environmental sound levels analysed in 10s intervals for the mean, minimum and maximum sound volume showed no clear correlation between the different rounds of the experiment.

A second vehicle based experiment was carried out on four different types of roads (suburban, rural, urban and high speed). Additional sensors were installed on the car used for the experiment including pollution sensors, microphone, car axle accelerometer and ambient light sensors.

## 1. INTRODUCTION

Many navigation applications have now become solely reliant on Global Navigation Satellite Systems (GNSS) so that there is no longer a backup when the signals received from GNSS are limited or entirely unavailable [1]. Therefore if there is interference to the signal, navigation capabilities can be lost or become misleading. This interference could be caused deliberately or accidentally. The increasing use of "personal privacy" devices to defeat GNSS-based tracking has made short-range jamming more prevalent, whilst the increasing demand for radio spectrum could make adjacent channel interference a greater threat. GNSS performance can also be degraded in dense urban areas by blockage and reflection of the signals by buildings.

Where a robust and reliable position solution is required, GNSS must be combined with other technologies. All navigation and positioning techniques are based on one of two fundamental methods: position fixing and dead reckoning. Position fixing techniques, such as GNSS, determine position directly using identifiable external information, whereas dead reckoning measures the distance and direction travelled from a known starting point [2].

There are many dead-reckoning techniques, most of which are limited to certain applications. Inertial navigation, which works by integrating measurements from accelerometers and gyroscopes, can potentially be used for any application, but high-performance sensors are expensive. For road navigation, odometry, which measures the rotation of the vehicle's wheels, is also commonly used. This may be combined with a gyroscope for turn detection and accelerometers for detecting wheel slip. However, all dead-reckoning techniques suffer from the problem that the accuracy of the position solution degrades with time due to the accumulation of sensor errors. Therefore, dead-reckoning is commonly integrated with GNSS, with GNSS constraining the growth of the dead-reckoning errors and dead-reckoning bridging outages in the GNSS position solution [2]. However, dead-reckoning is only suitable for bridging short outages. For robustness against longer GNSS outages, alternative position fixing techniques are needed.

Position fixing systems can use either man-made signals or environmental features to provide the information they require to determine position [2]. Most signal-based systems use radio and there are many alternatives to GNSS already. Most smartphones are capable of positioning using mobile phone and Wi-Fi signals, as well as GNSS. However, many "personal privacy" devices jam these signals as well as GNSS. Enhanced Long-range Navigation (ELoran) is difficult to jam, but is only available in a few countries (including the United Kingdom) and can exhibit large errors in urban areas due to re-radiation effects [3]. Navigation using broadcast signals of opportunity is not yet mature, whilst most other radio positioning techniques are designed for either air or indoor navigation.

For land navigation in particular, a new approach is therefore needed and environmental features provide a potential source of location information. Environmental features include buildings or parts thereof, signs, roads, rivers, terrain height, sounds, smells, and even variations in the magnetic and gravitational fields [2]. In recent years, there has been a lot of interest in visual navigation techniques for land vehicles and pedestrians [4, 5]. Visual navigation can be highly accurate, but is also a highly complex problem and research is still ongoing to make it robust.

A different approach to environmental feature matching, using a variety of features to provide relatively sparse and simple positioning information is therefore proposed with the sparseness of individual features compensated by using multiple feature types; integrating the feature-matching with dead reckoning providing robust positioning.

The overall solution is to place hardware within a batch of vehicles, comprising multiple sensors, (the exact combination to be from a feasibility study), a GNSS receiver and sensors for dead reckoning. Road map matching could also be included. During normal usage the GNSS receiver is used for positioning and a database is updated with the feature information from all the sensors accompanied by location stamps from the GNSS-based position solution. As the multiple vehicles travel around an area the database is built up for these routes. In the event that the GNSS receiver does not receive sufficient signals to maintain an accurate position, the database is called upon for navigation by environmental feature matching. The sensors will continue to take measurements and by combining the knowledge of last known location, dead reckoning and the sensor`s outputs, the positioning algorithm will draw upon the database to output an estimated positioning solution. This method is shown in Figure 1.

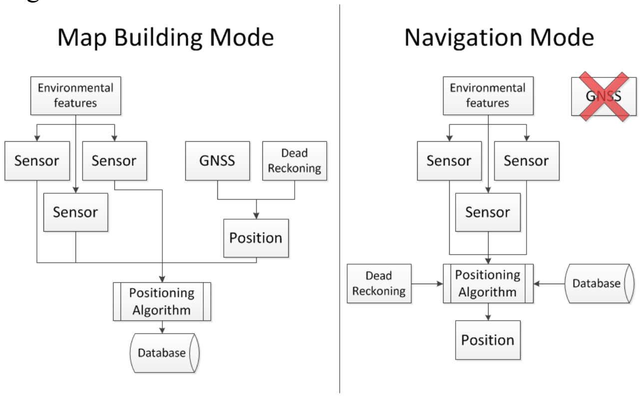


**Figure 1 - Basic workflow modes for collecting data and navigation by the collected data**

This navigation system relies upon the roads being travelled on a regular basis so that the 'maps' created from the sensory outputs are kept up to date and therefore valid. The most likely users for this technology would be fleets of vehicles that can share the mapping information. To focus on a typical system, use in emergency vehicles was considered. Knowing your position is vital in an emergency vehicle and a system that incorporates a back-up to GNSS would be advantageous. The motivation for maintaining a continuous positioning solution is that, when moving within a complex environment, it is necessary to maintain the integrity of the current position. In emergency situations, delays are not acceptable and integrity is vital and there is no point in time when the vehicle can be delayed to obtain a position fix.

Although it is supposed that this system would be used by emergency service vehicles such as ambulances and police cars it could also be used in wider applications such as fleet management and tracking devices. Ultimately, crowd sourcing techniques could be used to pool information from all the different vehicles equipped with the system. With a very large number of vehicles maintaining the feature database, the system could adapt to changes in the environment very quickly.

The scenario on which the project will focus is as follows:

> *The detector must be installable on a road vehicle (with particular focus for use in an emergency vehicle), at a reasonable cost with minimal alterations to the vehicle. Continuous coverage is not required because the measurables will be used in combination and integrated with dead reckoning. GNSS will be used as the reference position to create the measurable maps when available.*

This paper presents the results of a feasibility study to determine which combination of environmental features and sensors should be used for the proposed navigation system. Many of the features considered have never been used for road navigation before. Section 2 summarises an initial literature-based assessment of 15 different classes of environmental feature. Section 3 describes an initial pedestrian experiment conducted to assess the variability and repeatability of a selection of different feature types. Section 4 then presents the results of road vehicle experiments, investigating a wider range of environmental features. Section 5 draws conclusions on the three stages of the feasibility study. Finally, Section 6 sets out the next steps of the project.

## 2. LITERATURE-BASED FEASIBILITY STUDY

The environment consists of numerous features that could be measured such as road signs, magnetic fields or gravity. Navigation by environmental feature matching requires both features to observe and sensors to observe them with. However, a feature can be measured in multiple ways (e.g. road texture can be measured using light or sound or vibrations) and a single sensor could measure multiple features (e.g. a magnetometer can measure both the Earth's magnetic field and magnetic anomalies due to metal structures). The term 'measurable' is used here to describe an attribute of the environment that encompasses both the feature and how the signal from this feature is measured.

### 2.1 Choosing the features and sensors

The initial step was to brainstorm possible environmental features regardless of potential practicality.

One way of categorising the features is to group them according to the type of output that comes from the sensor. The three groups are: continuous, discrete and discrete with background.

Continuous features have a value at all positions (for example, height). Discrete features occur only at one position (for example, road signs) but might also be detectable remotely resulting in a localised continuous feature such as range or direction to the discrete feature. Discrete with background features occur where anomalies in a continuous feature occur at discrete positions. Pattern matching positioning techniques can be used for all of these feature types but discrete features also offer the capability to use proximity, ranging and angular position derivation [2].

The five broad criteria that were used to evaluate each of the environmental signals were:

- Temporal Variation
- Conformity to Scenario
- Ambiguity
- Precision
- Coverage

Temporal variation is not a desirable feature in a signal. In order to create a map, it must be possible to predict the value from a sensor at a particular location. If there is temporal variation this will become more challenging or even impossible (if the temporal variation is random). If there is predictable temporal variation it may be possible to still use the signal if the algorithm is modified to take into the account the time variation pattern.

A feature/sensor combination must be suitable for the projected scenario. Here they have been assessed in relation to the scenario outlined in section 2.

Ambiguity is found when a value measured by a sensor is not unique at a particular location. In the ideal case, there would be a value available at every point and this will be completely unique to that location. It is important for a signal to have low ambiguity as high ambiguity increases the uncertainty in the position of the device.

Precision is defined as:

> *'A quality associated with the spread of data obtained in repetitions of an experiment as measured by variance; the lower the variance, the higher the precision. The precision of an estimator is measured by its standard error.'* [6]

As the technique being devised creates maps with the same sensors that will be used to predict the current position (when called upon) it is only important for the similar values and changes to be measured at the same position each time, not for those values to be accurate for that location.

Coverage relates to the proportion of space within which the signal provides useful information for navigation. This does not include a consideration of the accuracy of the positioning solution in this space. Coverage will only be considered over an area where there are measurable changes. For example for terrain height changes, there will be greater coverage if there are hills compared to flat plains.

### 2.2 The features

A selection of the features assessed are discussed in this section and followed by a table ranking all of the features which were considered. Radio wave signals have been removed from the scope of this paper as several technologies currently exist and are commercially used. It is possible that an end product could also make use of techniques such as ranging using FM radio waves or using Wi-Fi fingerprinting but are not directly studied in this paper.

#### 2.2.1 Gravity

The force on an object in the Earth`s gravitational field is fairly uniform across the surface but with adequately sensitive sensors the variations in the force can be measured [7]. There will be very low temporal variations as objects that make small changes to gravitation field strength need to be extremely large structures which are unlikely to move or change over the time frames of use for this navigation technique. Gravity is present across the globe and its accuracy is independent of population density so could be used in urban or rural environments.

A new generation of smaller and more precise gravity gradiometers is being developed using cold atom technology [8]. Such sensors would be useful for this project's aims however it will be many years before they will be available for use in road vehicles.

A limitation of this method could be that the differences in the gravitational field strength from one location to the next is so minute that there may not be the necessary variation to create a map which produces unique map matches. A typical submarine gradiometer will have precision up to 400m [9]. Also the size of the sensor is large (a GT-2M marine Gravimeter is 400mmx400mmx600mm [10]) and extremely expensive (several hundreds of thousands of dollars). For the uses in this project these are all prohibitive.

#### 2.2.2 Ambient light

There are two options for measuring the ambient light levels. One is to use a simple photo-diode that reads the intensity of the light. The other is to use a camera which has greater resolution but may give a more complex interpretation of the ambient light. Experimentation could show that the photo-diode give sufficient information on the light intensity that more complex measures are not needed.

As day and night will have very different light signatures, there will need to be separate treatments for these two time-frames. For example, an issue for daytime measurements is that weather conditions could skew the measurements. When there is broken cloud cover, the sun can move behind clouds creating variability and unpredictability in the light intensity.

An alternative use of a light intensity sensor is to provide a heading measurement. The time of day will be known and so the direction the car is travelling can be derived. Also shadows rotate throughout the day in relation to the sun`s movement in the sky. It may be possible to use the presence of a shadow by using a similar technique to GNSS shadow matching for urban canyons [11, 12]. By knowing the time of day and the height of the buildings a map could be made of the position of the shadows.

#### 2.2.3 Magnetic field

Human-created magnetic fields are produced by numerous objects and devices in an urban area. For interior environments, magnetic field anomalies have been used for the navigation and there are several studies looking into the use of this [13, 14, 15]. There are fewer studies into the use of magnetic field anomalies in an exterior environment. Shockley et al. [16] used a magnetometer in a car. They used a particle filter method to assist with the ambiguity and uncertainty of the magnetic anomaly landmarks. By using this technique the ambiguous locations information could be narrowed down during travel as certain positions became more likely. The study created the map using a GNSS receiver and then in navigation mode only used the magnetometer.

There have been studies on using the variations in strength of the Earth's magnetic field to produce a position solution [17]. The benefit of this is that true Earth magnetic field is more widespread (only 5% of what is measured will be due to anomalies). The drawback for using this element of the magnetic field is that the precision (as defined in Section 2.1) is lower compared to the anomaly data.

### 2.2.4 Scent

Some animals have evolved to use scent for navigation such as salmon or ants [18, 19], while other animals use scent for detection such as dogs. With the progression of technology, electronic noses are being used in such industries as food preparation and medicine [20] and although currently they are not used in positioning it may be possible when technology improves.

Sensors can be used to detect individual 'scents' or particulates or more complicated mixtures of particulates. From the cost perspective the detectors (mass spectrometer) that can detect and compute the complicated mixtures of particulates that humans would recognise as a specific smell (e.g. a fish and chip shop) would be out of the price range for this project; in the range of a few thousand to tens of thousand pounds. These sensors also tend to be too bulky for our application.

Examples of sensors that only detect very specific particulates are sensors that detects odorous VOCs (Volatile Organic Compounds) [20] or a carbon monoxide sensor. Both would cost around £10-£20 and have dimensions of 2x1x1mm.

The weather conditions are likely to have a large effect on the detection of scents. If there are windy conditions then the scent could be reduced or increased depending on the wind's direction.

### 2.2.5 Road signs

Text could be identified from the visual environment; this could be street signs, shop names or warning signs [21]. In the present context a sign is defined as an area of text in an enclosed shape or a sign from the British government traffic signs website [22]. This could be expanded in future work to with other sign sets. Figure 2 shows some examples of street signs in Great Britain. Consistency of text font and background colours will assist in the recognition of the signs.


**Figure 2 - Example road signs. Crown Copyright [22]**

An issue with this technology could be that signs can be obscured from view by road furniture or other vehicles. Also the signs will be not necessarily perpendicular to the camera and so will result in skewing of the text. An earlier study [23] investigated this by first finding the plane of the sign's text and manipulating the text before 'reading' the sign.

Low lighting conditions make the apparent contrast between the different colours on road signs lower for the human observer. Many studies use HSI (Hue, Saturation and Intensity) colour space compared to RGB (Red, Green and Blue) as 'visibility' is less affected by light conditions. As electronic sensors usually respond to photon energy, radiometric measures are more appropriate in this context for matching because contrast may be invisible to the human eye, but measurable in terms of the light emission [24].

### 2.2.6 Temperature

There is a variation in temperature over several days (particularly in the temperate climate of Britain) and also within a single day. The underlying pattern of spatial variation may still be detectable. Open areas are likely to be cooler as they are more open to the wind and subsequently enclosed areas warmer. Depending on the type of surfaces in the local environment, heat may be re-emitted later in the day once the air begins to cool. Another effect found in urban areas is due to the high concentration of heated buildings and their heat leaking into the external environment.

This environmental feature will need some very careful consideration to be successful as different seasons; times of day and the effect of the temperature of the vehicle will all have undesired effects on the readings.

The sensors (thermometers) have a response time that could mean that the temperature is not updated quick enough to provide an accurate reading of the temperature for a specific location. The response time for a middle range thermometer is 1-2.5s [25] which could be too slow for a vehicle that is likely to moving at over 13m/s (30 mph) on average.

### 2.2.7 Terrain Height

Terrain-referenced navigation (TRN) determines position by comparing a series of measurements of the height of the terrain below a vehicle with a database known as a digital terrain model (DTM) or digital elevation model (DEM). Sensor biases may be eliminated by matching the terrain height variation instead of the absolute height [2]. TRN has been used for many decades for air navigation and, in more recent years, has also become established for marine applications, particularly underwater vehicles.

For land vehicles and pedestrians outdoors, the navigation system generally maintains a constant height above terrain and most journeys have fluctuations in height along their route. A barometric altimeter may be used to measure variations in terrain height. Furthermore, an IMU could smooth the noise from the barometric solution. Thus, in principle, TRN may be performed [26, 27]. However, as the host vehicle or user speed is much lower, a high-resolution database is needed to capture sufficient terrain height variation to determine position. With the navigation concept proposed here, this problem is circumvented as users build their own databases.

#### 2.2.8 Road Texture

There are multiple different road surface materials that have been used on British roads which depend on the road use and the maintenance body's preference. Each type of surface produces a different driving experience that could be detected in a number of ways.

A change in vibration caused by the road surface could be used to detect the seams between two road surface types. This may be easier to detect than the actual texture of a single road surface texture. Similarly, potholes could provide discrete references, albeit not long lived.

Weather could be an issue. Depending on the method for measuring the road texture, water or snow could significantly alter the measurements. Snow in particular would mask the road texture and water would fill dips in the road surface.

There are existing technologies that automatically detect cracks and weaknesses of road surfaces and these could be modified to determine the texture of the road surface. The current limitation of the technology is that the road maintenance authority will usually have custom made vehicles whose design is optimised to this single process [28]. It may not be possible to have the same effectiveness without the custom made vehicle.

An alternative method is to use microphones, placed near the wheels of the car and detect the noise level caused by the contact of the wheels with the road surface. A study found that there was considerable difference in the sound created by cars travelling on different road surface materials [29].

#### 2.2.9 Vehicle Movement

The specific movements of vehicles could be used to determine position. For example movements of a vehicle around a roundabout would give a measurable signal in the horizontal plane of an accelerometer. This may also be seen when there are speed restriction methods that involve a slalom manoeuvre in the road and the traffic in a specific direction giving way to oncoming traffic. An issue for the accelerometer is the speed that these turns are made at. As a signal, it will be more pronounced if it is taken at speed. It may be possible to mitigate this by averaging the signal.

#### 2.2.10 Other features

The remaining features that were reviewed were radioactivity, environmental sounds, wind speed, pulsars, vehicle speed and celestial.

#### 2.2.11 Ranking

The environmental features are scored out of 5 for Temporal Variation (T), Conformity to Scenario (Cf), Ambiguity (A), Precision (P) and Coverage (Cv) and totalled (Tt) to give the overall score. Table 1 shows the features in order of overall score.

**Table 1 - Scores for features**

| Feature | T | Cf | A | P | Cv | Tt |
|---|---|---|---|---|---|---|
| Road Signs | 5 | 4 | 3 | 4 | 4 | 20 |
| Terrain Height | 5 | 5 | 3 | 3 | 3 | 19 |
| Ambient Light | 4 | 5 | 2 | 3 | 3 | 17 |
| Vehicle Movement | 4 | 4 | 2 | 4 | 3 | 17 |
| Magnetic Field | 3 | 5 | 2 | 3 | 4 | 17 |
| Celestial | 3 | 3 | 5 | 1 | 3 | 15 |
| Road Texture | 3 | 4 | 2 | 4 | 2 | 15 |
| Scent | 2 | 5 | 3 | 2 | 2 | 14 |
| Temperature | 1 | 5 | 2 | 1 | 3 | 12 |
| Radioactivity | 2 | 5 | 2 | 2 | 1 | 12 |
| Gravity | 5 | 2 | 3 | 1 | 1 | 12 |
| Vehicle Speed | 1 | 4 | 1 | 2 | 3 | 11 |
| Environmental Sounds | 1 | 2 | 2 | 3 | 1 | 9 |
| Pulsar | 5 | 1 | 3 | 0 | 0 | 9 |
| Wind Speed | 0 | 4 | 2 | 2 | 0 | 8 |

## 3. PEDESTRIAN EXPERIMENT

### 3.1 Motivation

After carrying out the literature-based feasibility study, the next step was to conduct a preliminary experiment to determine the usability of a selection of the identified environmental features. The pedestrian experiment was designed to consider three criteria: ambiguity, precision/temporal variation and coverage.

An understanding of the temporal variation and precision can be established by repeating a route multiple times and over multiple days. By comparing the measurements collected it will show how much the features change and within what time frame.

Ambiguity can be tested by examining the frequency of ambiguous sensor outputs along the route. As part of this procedure, processing options will be analysed to reduce the effects the ambiguities have on determining location.

Coverage will be assessed based on one of two methods depending on the type of feature. For continuous-type features the signal to noise ratio will be used. This will give an approximate understanding of the resolution of the position solution on a sensor output map. For those features that comprise separately observed landmarks, coverage is calculated by how often landmarks are seen.

### 3.2 Sensors used and setup

Two pieces of apparatus were used for the initial experiment and these are shown in Table 2.

**Table 2- Sensors used in Pedestrian Experiment**

| Sensor | Make & Model | Contained Sensors | Feature |
|---|---|---|---|
| Inertial Measure-ment Unit (IMU) | Xsens MTi-G | Barometer | Terrain Height |
| | | Accelerometer | Dead Reckoning |
| | | Gyroscope | Dead Reckoning |
| | | Magnetometer | Magnetic Field |
| | | Thermometer | Temperature |
| | | GNSS Receiver | GNSS Signals |
| Video Camera | Panasonic SDR-H81 | Video | Road Signs |
| | | Sound | Environmental Sounds |

Two experimenters partook in the experiment. The Inertial measurement unit (IMU) was on a flat board which was rested at waist height of the first experimenter, see Figure 3. The GNSS antenna was attached to a hat on the head of the first experimenter. The second experimenter carried the laptop connected to the Xsens and held the camcorder. The Camcorder was placed at shoulder height of the first experimenter and was pointed to obtain the same view as the first experimenter perceived.

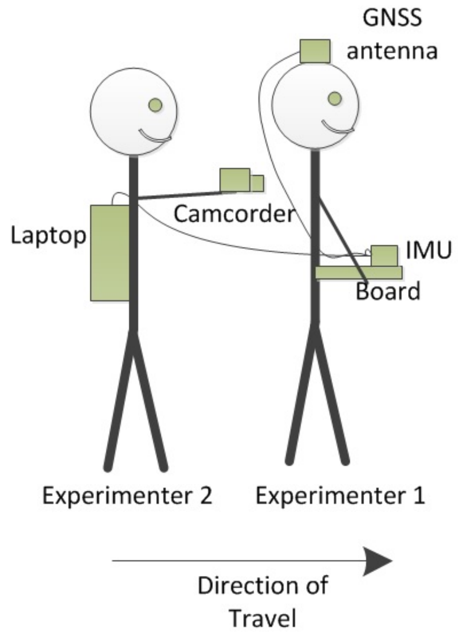


**Figure 3 - Position of experimenters and equipment**

### 3.3 Method

The video recorder filmed the turning on of the IMU. This was used to synchronise the video footage time to the IMU time. The route walked can be seen in Figure 4. The experimenters completed the experiment in an anticlockwise direction.


**Figure 4 - Path of experimenters including Pavements and Crossings used. Green dot is starting position. ©Microsoft Bing**

During the journey the 2 experimenters carried the sensors as described in Section 3.2 and followed the same position on the footpath and crossed the roads at the approximately same point each round. The experiment's route was repeated three times and there was a 3-4 minute delay between each of the rounds.

All data was post processed for the experiment. The experiment was repeated in a clockwise direction on a separate day. The results of the clockwise experiment are not shown in this paper as the results achieved were very similar to those of the anticlockwise experiment.

#### 3.3.1 Position Determination

A truth model for position was created using Bing maps' [30] longitude and latitude measurements at each corner. Each loop of the experiment had a total distance of 1213m as calculated from the directions function on Bing Maps. Combining this with the time taken from the camcorder, the average speed was calculated to be 1.22m/s. This speed varied due to obstacles, crossing of roads with traffic and natural walking speed variation which were all observable on the camcorder footage.

The integrated position solution, provided by the GNSS receiver and IMU, shows the broad structure of the route followed (Figure 4). The worst position tracking is at the end of the journey. This can be clearly seen as the trace with a large erroneous loop.

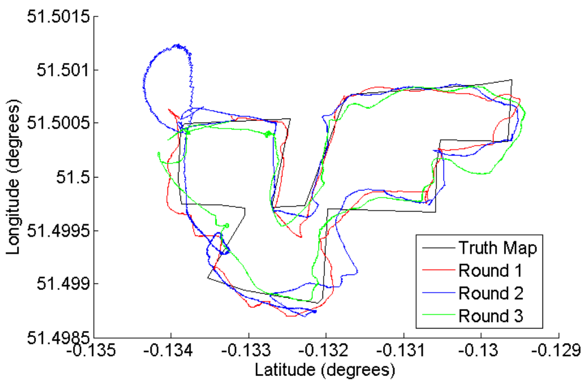


**Figure 5 – Integrated GNSS/IMU Position with Truth Map**

The mean deviation from the corners is 47.5m and the maximum distance from the truth model is 231m on round two for the corner at (-0.1321,51.5).

The deterioration of the traces shows the limitations of GNSS (and MEMS (Micro-Electro-Mechanical Systems) IMU) in a highly urbanised area. Therefore it was not used as a truth reference and an alternative method was found. This method involved finding the position of the corners from a map and recording arrival times at these corners, from the sensor data. These were then used to determine the distance along the whole route by interpolation. It was assumed that the speed of the experimenter on each stretch between corners was constant.

On average there was 63s/ 84m between each corner and a total of 14 points where the position and time could be correlated and used for the distance interpolation.

The steps taken to calculate the assumed position at a given time are shown below.

- Remove the IMU data before and after the period spent walking (using the initialisation technique recorded on the video camera).
- Using the video footage, note the time-stamps for the corners within each of the rounds.
- Using the longitude and latitude references of the corners (from Bing Maps), convert to the distance between corners ($\delta r$) using the formulas below.

  $$\delta L = (L_{end} - L_{start})$$
  $$\delta\lambda = (\lambda_{end} - \lambda_{start})$$

  $$a = \sin^2\left(\frac{\delta L}{2}\right) + \cos(L_{start})\cos(L_{end})\sin^2\left(\frac{\delta\lambda}{2}\right)$$
  $$c = arctan_2(a^2, (1-a)^2)$$

  $$\delta r = Rc$$

  where $L_{end}/\lambda_{end}$ and $L_{start}/\lambda_{start}$ is the latitude/longitude at the start and end of the distance being measured. $R$ is the mean radius of the Earth.

- Linear interpolation was used to approximate the time the experimenters were at positions between corners. Using linear interpolation assumes that the experimenters walked at constant speed between corners [31].
- The time-stamp associated with the sensor outputs was replaced with the newly calculated distance from the starting point.

### 3.4 Results

#### 3.4.1 Road signs

A `sign' could be text contained within a enclosing shape or common traffic sign symbols in the environment such as shop signs, speed limit signs etc. Therefore it is not just limited to official road furniture. The road signs were observed by eye from the video footage. Once a sign was discernible from the footage, the time stamp was noted and the sign was described. It was also noted if the sign was the same type and context as one seen earlier in the round.

Within the footage taken by the camcorder some sign types were seen more than once, for example, stop sign at the road junction. Therefore a duplicate is defined as a sign that could not practically be distinguished from an earlier sign.

There were 70 signs (including duplicates) seen on any one of the three rounds and there were 53 unique sign types seen on any one of the rounds. Therefore 24% of signs were duplicates. Signs were not seen every round due to obstructions and mobile signage. For example only 46% of signs were observed on every round. Over the three rounds it was found that, on average, any particular sign is seen 76% of the time.

##### 3.4.1.1 Treatment of duplicates

As approximately a quarter of the signs were a duplicate of an earlier sign, the treatment of duplicates has a great impact on how successful the navigation is. For this experiment, three methods were proposed.

1. Assume no duplicates
   - Assume that the future road sign reading software will be able to discern the differences between the same sign type.
   - It may not be feasible in practice but it provides a baseline to compare the other methods with.
2. Use signs in pairs
   - Assume the each sign is part of a consecutive pair, and treat a pair as a single landmark.
   - A pair is created from the sign before and current sign and another pair from the current sign and next sign.
3. Do not include signs that are duplicated
   - Disregard the sign if a duplicate is seen
   - In practice, signs will only be disregarded within a certain distance between the duplicates. For this short experiment any duplicated are disregarded.

Table 3 shows the average time between unambiguous signs based on the 3 methods. The idealised no duplicates method in terms of coverage had the least time between signs and the ignore duplicates method was the worst method as it consistently gave the longest time between signs.

**Table 3 - Average time between each Sign depending on Method used**

| Anticlockwise | No Duplicates | Paired | Ignore Duplicates |
|---|---|---|---|
| Round 1 | 16s | 20s | 24s |
| Round 2 | 16s | 20s | 23s |
| Round 3 | 15s | 17s | 20s |
| At least 2 Rounds | 16s | 22s | 24s |
| All Rounds | 24s | 41s | 27s |

The results show that there is between 15s and 24s between signs at a walking pace. If this is extrapolated to a car travelling at 13m/s (30 mph) then there would be only 1.5s to 2.5s between each sign. This would give a potential position update rate of every couple of seconds.

To determine the precision of observing the signs over multiple rounds, the difference in the observer position when a sign was first seen on particular rounds was compared. In the clockwise direction there was an average 21m between the positions related to the same sign on different rounds (the rounds chosen are the two rounds that have the most difference in position). The two main causes of this observation discrepancy are the limitations of the method used to convert time to position and also variability of when the signs are first seen. Thus there is considerable scope for improvement.

### 3.4.2 Terrain Height

The altitude solution from the IMU uses GNSS and barometer outputs and has a manufacturer's accuracy of 8m CEP [32]. For the proposed system it will be necessary to obtain an altitude solution without using GNSS. However for this initial experiment a GNSS aided solution was used.

The variation in the height was approximately 10cm during the experiment. This means that the terrain in this experiment did not have sufficient variation for the sensor to detect. As the movement of a human walking or a car`s suspension would include variation of the order of 1-5cm, the variation in true height may not have been discernible above the noise from travelling even if the sensor was sensitive enough. This experiment's terrain is therefore not suitable for using height as a measurable.

Figure 6 shows the height output from the Xsens above sea level. The figure is based on both GNSS and the barometer. The barometer has a large slowly varying bias which is constrained by the GNSS signals.

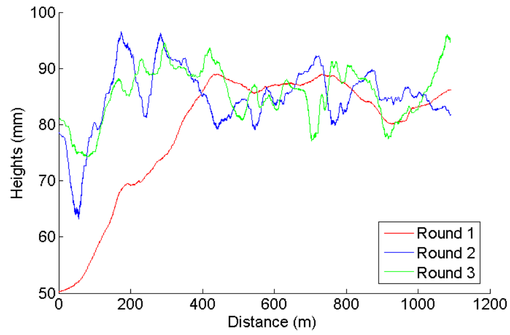


**Figure 6 - Height Changes given by integrated GNSS/barometer**

### 3.4.3 Magnetic Field

The raw magnetometer data shows the sum of the Earth's magnetic field and the fields caused by the local environment. By taking the magnitude of the magnetometer data the majority of the effects of the heading-dependent field measurements are removed due to the magnetic field being measured in the body-frame. Some of the residual equipment magnetic field will remain [2]. Figure 7 shows that the peaks occurring at the same positions along the route for all three rounds. Figure 8 shows a zoomed in version of Figure 7.

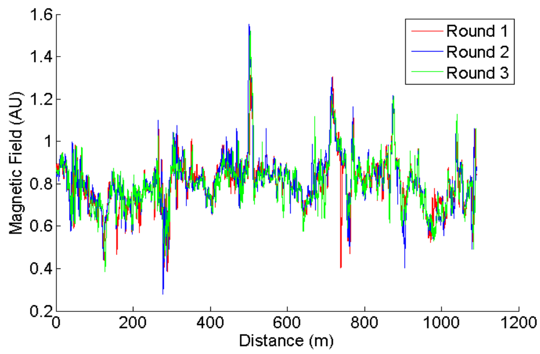


**Figure 7 – Magnitude of 3-axis magnetometer measurements**

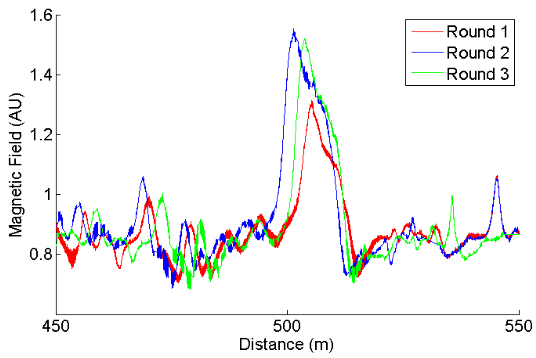


**Figure 8 - Zoomed in portion of Figure 7**

The position of the peak is taken from the highest point to the baseline. Therefore the baseline (average level of the background magnetic field) needs to be determined. This was done by computing the 10th degree polynomial to find the changing base level of the magnetic field ignoring the peaks. Then, heuristically, a threshold was chosen whereby if a value is above this threshold it is considered part of a peak. The threshold was chosen at 0.3A.U. (arbitrary units) because this balanced the need for a large number of peaks with the need to ensure that erroneous peaks are not included due to the noise associated with the background magnetic field.

In total there were five peaks found per round for this chosen threshold. Averaging over all the peaks there was a maximum difference between the positions of same peaks over the three rounds of 3m. It should be noted that some of this variance may be caused by the errors associated with the interpolation method converting time to distance.

There is also a continuous element to the magnetic field (background magnetic field level). Therefore it is important the peaks can be distinguished from this background. The peak to background ratio analysis is shown in Table 4. Peak height is the height of the largest peak as defined above. The background noise level is determined by taking all values below the threshold (i.e. non-peaks) subtracting the corresponding baseline value and then calculating the standard deviation of this.

**Table 4 - Calculation of the peak to background ratio for magnetic field anomalies**

| Analysis | Values |
|---|---|
| Maximum Peak Height | 0.67 A.U |
| Background Level | 0.07 A.U. |
| Peak/Background | 9.6 |

There were five magnetic field peaks each round, which means that on average there was a peak every 240m. Extrapolating this to a vehicle travelling at 13m/s (30 mph) there would be a peak every 19s.

### 3.4.4 Temperature

Temperature had been rejected in the literature review due to the expected high temporal variability. But using the thermometer incorporated into the IMU the temperature was analysed and it showed lower temporal variability than had been anticipated.

The weather during the experiment was that of a very warm British summer day (>30˚C) with no cloud cover or significant wind.

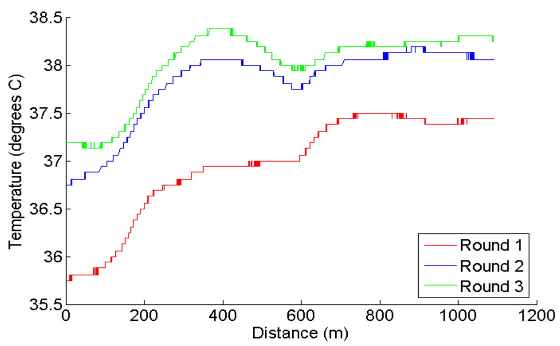


**Figure 9 - Temperature Profile from inbuilt IMU thermometer**

In the raw temperature data there is an absolute temperature increases for each round (Figure 9). Therefore the temperature within each round was normalised. The normalisation highlights changes caused by the environment rather than the overall increase in temperature as the day progressed during the experiment.

The signal to noise ratio is shown in Table 5 which also gives an approximation of coverage (as defined in Section 2.1). Noise is taken to be minimum resolution of the thermometer as stated in the sensor's specification [32]. The signal is taken as the overall temperature change from within a round (i.e. the difference between the minimum temperature and maximum temperature within a single round). Once this was calculated for the three rounds the minimum for the rounds was taken.

**Table 5 - Calculation of the Signal to Noise ratio for Temperature**

| Analysis | Values |
|---|---|
| Minimum Temperature Change | 1.25˚C |
| Maximum Temperature Change | 1.75˚C |
| Noise Level | 0.06˚C |
| Signal/Noise (min) | 20.8 |

It may be necessary to carry out the experiment again in different conditions to verify if the correlations of the temperature traces are not entirely dependent on summer day conditions. It is also possible that the temperature could have been affected by the other sensors in close proximity within the IMU. A standalone thermometer may reduce the risk of interference.

### 3.4.5 Environmental sounds

Sounds from the surroundings were recorded using the Panasonic video camcorder. The sound was analysed in 10s (non-overlapping) intervals and in those intervals the mean sound levels were found. This was done for both the right and left microphones and Figure 10 shows the output from the left microphone. Although there was difference in the sound levels experienced for the two microphones, there was no consistency between the sound levels heard in a particular microphone between the different rounds due to microphone directionality. Figure 10 shows the output from the left microphone.

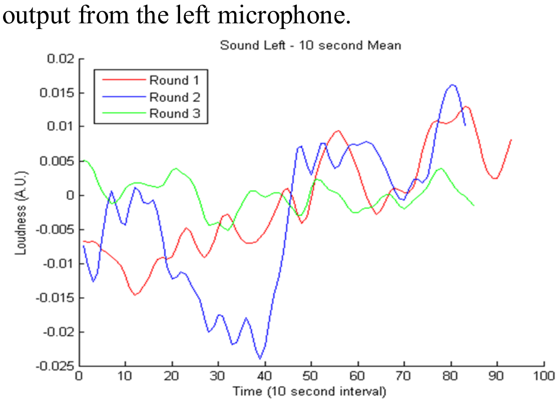


**Figure 10 - Sound signal for 10s intervals for mean sound level for left microphone**

The environmental sounds observed during the experiment are a mixture of car noise, road works, and people. From the analysis performed there is very little consistency in the noise levels between the rounds in this urban environment.

# 4. ROAD EXPERIMENT

## 4.1 Motivation

The next step after the initial pedestrian experiments was to run the equivalent experiments, using a road vehicle. As more sensors can be carried by the car than a pedestrian the number of sensors used was increased. The aim of the experiment was to assess as many as possible of the sensors-feature combinations that were judged to be potentially viable in the literature review stage and pedestrian experiment.

The criteria used to judge the success of a feature in the road experiment were: correlation, variation of landmark position and coverage. Correlation is used to quantify trace similarity along the same route. Variation of landmarks is used to establish the precision of the position determination using landmarks and coverage is a measure of the resolution of the signal above noise or background levels.

## 4.2 Sensors used and setup

The sensors used in this experiment can be seen in

Table 6.

**Table 6- All sensors used in the road experiments**

| Sensor type | Sensor name | Feature |
|---|---|---|
| Accelerometer | ADXL345 | Road Texture |
| Air Quality | SEN01111P | Scent |
| Barometer | BMP180 | Terrain Height |
| Dust | GP2Y1010AU0F | Scent |
| GNSS | Xsens MTi-G | GNSS Signals |
| Light Sensor | Yocto-Light | Ambient Light |
| Magnetometer | Terrafix inertial compass 10000/1 | Magnetic Field |
| Microphone | Phidgets1133 | Road Texture |
| Thermometer | Yocto-Temp | Temperature |
| Video Camera | Panasonic SDR-H81 | Road Signs |

## 4.3 Method

In overview, a set of sensors with a GNSS receiver were attached to a car and driven in closed loops around Stoke-on-Trent on multiple road types over multiple days. The loop was repeated three times on each day on four road types and then repeated over three consecutive days. A Vauxhall Insignia car (mid-range hatchback) was used for the experiment and can be seen in Figure 11.

**Figure 11 - Vauxhall Insignia**

The four road types were suburban, urban, rural and high speed road. The route taken and a view from Google Street View showing the general type of landscape travelled through can be seen in Figure 13. Each route was designed to take between 15 and 25 minutes.

The accelerometer, air quality sensor, barometer, dust sensor and microphone interfaced with an Arduino microprocessor which was used to output the signals from the sensors to a laptop. The video recorder filmed the turning on of the IMU, Arduino, yocto-sensors and the Terrafix inertial compass to assist with synchronicity. During the car journeys there were two experimenters, one to drive the car and another to monitor the sensors.

There was 5-10 minutes between each round, where the sensors would be turned off and then restarted. The equipment was designed for the outputs of the sensors to be post-processed.

## 4.4 Results

### 4.4.1 Terrain Height

The height changes during a particular round were measured using a barometer. For the road experiment (unlike the pedestrian experiment) the height is measured without reliance on GNSS signals. Figure 12 shows the height changes detected for a rural road. A high level of correlation between the traces is clearly visible.

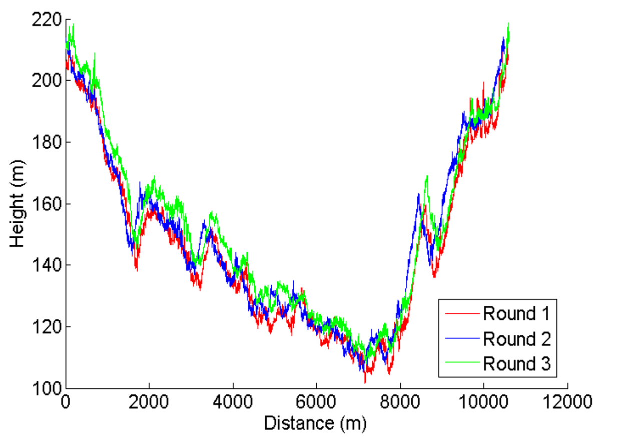


**Figure 12 - Height profile for rural road within one day**

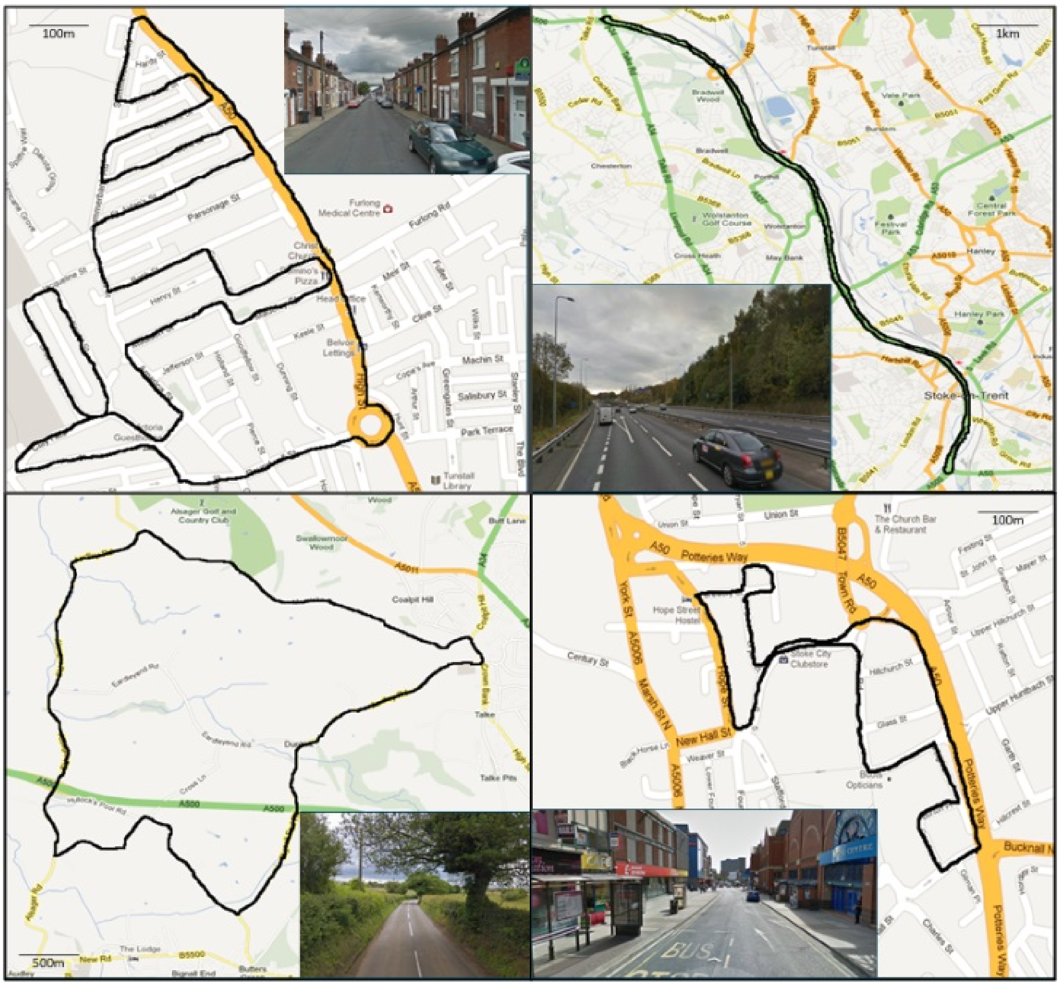


**Figure 13 - Road types used in road experiment with starting point and direction of travel in red. From left: urban, rural, high speed road and suburban © Google maps**

Depending on the type of road travelled there will be greater or lesser variation in height within a round. The road type with the greatest variation was rural roads with 119m maximum variation. To compare the variation a signal to noise analysis was carried out and can be seen in Table 7. This showed that the high speed and rural road had the greatest variation which contributes to the usefulness of the signal.

**Table 7 - Signal to noise analysis for barometer measurements**

| | High Speed | Urban | Rural | Suburban |
|---|---|---|---|---|
| Maximum Height Change | 102m | 37m | 119m | 47m |
| Noise Level | 2.5m | 2.5m | 2.5m | 2.5m |
| Signal/Noise | 41 | 15 | 48 | 18 |

To compare the precision and how much the measurements change over time it is appropriate to compare the measurements taken over the three days. Figure 14 shows the example height profile of the first, second and third day (all round 1) for the suburban road type. For this graph, a constant is added such that the minimum value for all three days is set to zero, because the weather differences affect sea-level reference pressure.

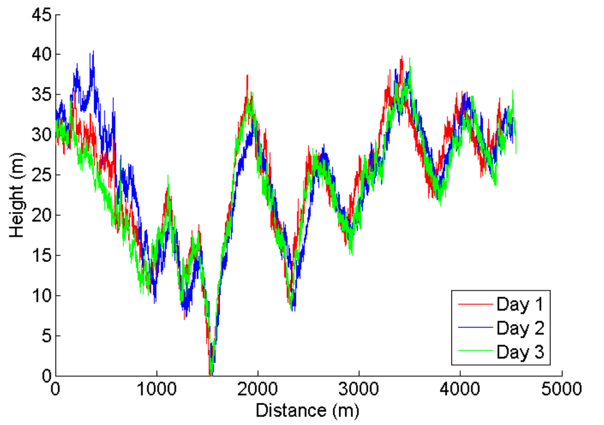


**Figure 14 - Comparison of height profile over 3 days with minimums set to zero**

Cross correlation was used to analyse how similar the traces were for the 4 road types. As there were three rounds each day there are three permutations that the cross correlation can be performed on (i.e. round 1 and 2, round 2 and 3 or round 1 and 3). These three cross correlation permutations were calculated for the data from the four road types. In Table 8, day 2 results were analysed and the cross correlation value shown is the average cross correlation found for the three permutations. The closer the value is to 1 is the greater the correlation.

**Table 8 - Cross correlation of height profiles**

| Road Type | Cross Correlation |
|---|---|
| High Speed | 0.88 |
| Urban | 0.95 |
| Rural | 0.99 |
| Suburban | 0.91 |

### 4.4.2 Magnetic Field

The magnetic peaks can be seen above the background level of the field. In order to distinguish between a peak and the background level a baseline and threshold were determined. This was done by computing polynomial up to 6th order (varied between linear and a 6th order polynomial due to varying nature of background magnetic field in different regions) to find the changing base level of the magnetic field. Then heuristically a threshold was chosen whereby if a value is above this threshold it is considered part of a peak. The threshold was chosen to balance the need for a large number of peaks with the need to ensure that erroneous peaks are not included due to the noise associated with the background magnetic field.

Figure 15 shows the magnetic field signal detected in the z-axis on the high speed road. Figure 16 shows a zoomed in segment of the previous graph.

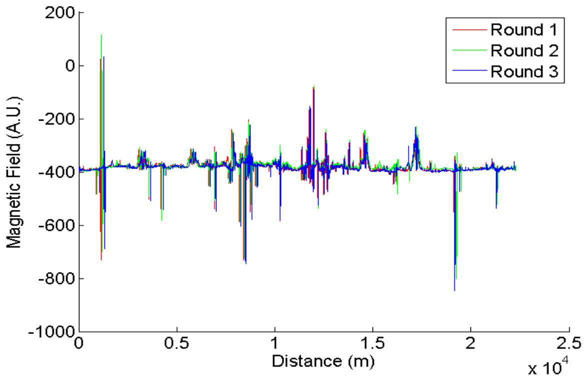


**Figure 15 - z-axis magnetic field profile for a high speed road**

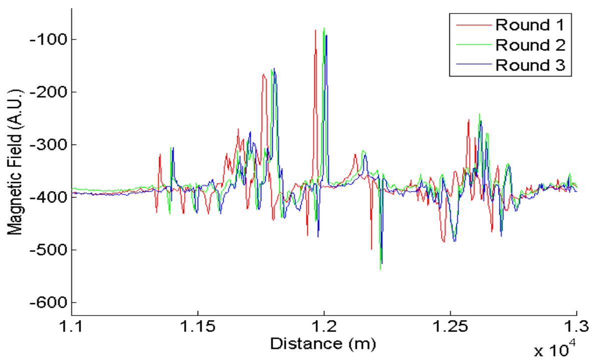


**Figure 16 - Zoomed in section of the z-axis magnetic field experienced on a high speed road**

Table 9 shows the number of peaks seen on average for a particular road type. It also shows the variance in the number of peaks seen on a particular day or round. It is for urban and suburban road types that there is the greatest variation in the number of peaks but the peaks also became broader and more difficult to distinguish on this road type. The high speed road gave the clearest peaks with a variance of 44m in the position of the peaks. The suburban roads gave the most peaks but also the most variation in seeing these peaks. Therefore there is a level of unreliability in these measurements on suburban roads.

**Table 9 - Analysis of the peaks (mean number and standard deviation)**

| | High Speed | Urban | Rural | Suburban |
|---|---|---|---|---|
| Mean Number of Peaks | 15 | 16 | 14 | 25 |
| Standard Deviation | 0.6 | 2 | 1.7 | 3.1 |

As with height a peak height to background level analysis was carried out for the road types. The standard deviation of the non-peak measurements was used as the background level. The ratios can be seen in Table 10.

**Table 10 – Peak height to background level ratio for magnetic field**

| | High Speed | Urban | Rural | Suburban |
|---|---|---|---|---|
| Average Peak Height | 125.7 | 41.9 | 29.8 | 48.3 |
| Background | 6.3 | 5.7 | 3.7 | 7.1 |
| Peak/Background | 19.9 | 7.4 | 8.1 | 6.8 |

This analysis shows that the peak heights on the high speed roads were greatest with similar background levels to the other roads and so gave the best signal to noise ratio. The other road types had similar peak to background ratios.

### 4.4.3 Temperature

During the experiment there was a mixture of sun and overcast conditions. One of the days there was intermittent very light rain.

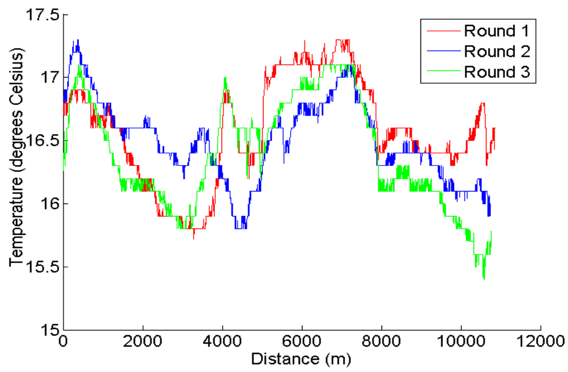


**Figure 17 - Temperature profile for rural roads**

Figure 17 shows the temperature signal experienced on the rural road type on a single day. This figure represents the road type that was the most cross correlated as seen in Table 11. The reason for this could be that with the car in the open air the temporal variation caused by other cars and buildings was limited. Suburban road showed no correlation and so highlights that temporal variation is linked to the environment being travelled.

**Table 11 - Cross correlation for temperature**

| Road Type | Cross Correlation |
|---|---|
| High Speed | 0.29 |
| Urban | 0.10 |
| Rural | 0.52 |
| Suburban | -0.05 |

The signal to noise ratio was determined to give an approximation of the coverage for temperature. This can be seen in Table 12.

**Table 12 - Signal to noise ratio for temperature**

| | High Speed | Urban | Rural | Suburban |
|---|---|---|---|---|
| Maximum Temp Change | 3.34 | 0.8 | 2.46 | 0.6 |
| Noise Level | 0.1 | 0.1 | 0.1 | 0.1 |
| Signal/Noise | 33.4 | 8 | 24.6 | 6 |

The signal to noise ratio was greatest for the high speed road and rural roads as these are the roads with the greatest temperature changes. This would also explain why there was low correlation for urban and suburban roads as there was insufficient variation to detect a pattern.

### 4.4.4 Road signs

Road signs were manually observed on the video footage and the full length of the footage for each road type was used to record the total number of signs seen on each of three rounds. Table 13 shows the number of signs seen for each road type and the rate these signs are seen (by distance and by time).

**Table 13 - Number of signs seen over full route**

| Road Type | No. of Signs | Meters between Signs | Seconds between Signs |
|---|---|---|---|
| High Speed | 280 | 75 | 3.6 |
| Urban | 165 | 14 | 2.8 |
| Rural | 45 | 239 | 21.9 |
| Suburban | 145 | 32 | 5.1 |

One-minute segments of different road types and rounds were observed and the time and type of signs was recorded. This was analysed to determine the number of signs that were duplicated and what percentage of the time an individual sign is seen over the rounds. Finally, the position where each sign is seen first is collected for each road type and the standard deviation calculated. Table 14 shows these results. It can be seen that although there is a greater number of signs on the high speed road because of the distance covered the position the sign is seen can be variable from round to round. Therefore the urban road with its lower speed showed a similar number of signs but far smaller position variance. Table 14 also shows that there seems to be a link between a larger number of signs in total with a higher percentage of repeated signs. This highlights the need for a comprehensive mechanism for deal with duplicates.

**Table 14 - Road sign analysis of 1 minute segment**

| | High speed | Urban | Rural | Suburban |
|---|---|---|---|---|
| No. Signs seen | 24 | 19 | 16 | 6 |
| % Duplicates | 65% | 59% | 27% | 33% |
| % Signs seen | 75% | 85% | 81% | 67% |
| Std Dev of Position | 105m | 39m | 59m | 34m |

### 4.4.5 Road Texture

**There were two sensors used to monitor the vibrations of the car in contact with the road and so indirectly measure the road texture. These were a microphone and an accelerometer. The cross correlation is shown in**

Table 15 and it can be seen that there is more correlation across the rounds in the microphone signal. Figure 18 and Figure 19 show a zoomed in section of the microphone and accelerometer signals for the rural road type.

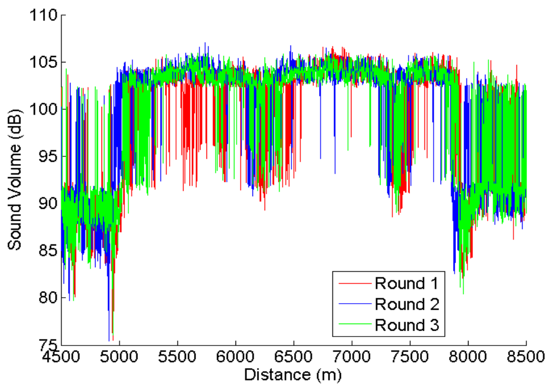


**Figure 18 - Profile from microphone attached to axle**

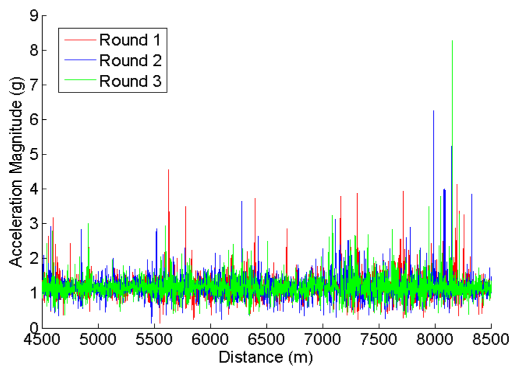


**Figure 19 - Profile from accelerometer attached to axle**

**Table 15 - Cross Correlation for vibration signals**

| Road Type | Accelerometer | Microphone |
|---|---|---|
| High Speed | 0.00 | 0.53 |
| Urban | 0.03 | 0.39 |
| Rural | 0.01 | 0.59 |
| Suburban | 0.01 | 0.17 |

It can be seen both from the cross correlation values and Figure 18 and Figure 19 that the microphone showed more similarities over the three rounds than the accelerometer. It may be possible to complete further analysis on the accelerometer data such as Fourier spectrum analysis which may highlight patterns that cannot be seen in the raw data.

### 4.4.6 Other signals

The signals from the light, dust and air quality showed less correlation as is shown in Table 16 are shown. Using this simple correlation method there seems to be little pattern between rounds.

**Table 16 - Cross correlation for signals from the light (L), dust (D) and air quality (AQ) sensors**

| Road Type | L | D | AQ |
|---|---|---|---|
| High Speed | 0.19 | -0.05 | 0.33 |
| Urban | 0.39 | 0.00 | 0.09 |
| Rural | 0.46 | -0.03 | 0.26 |
| Suburban | 0.26 | 0.07 | 0.16 |

A threshold, of having at least one road type with a cross correlation greater than 0.5, was used to determine which of the signals received greater investigation. Therefore further analysis was not carried out on light sensor, dust sensor or air quality sensor. With the current implementation of these sensors it has been assumed that these sensors could not be used in the final prototype.

## 5. CONCLUSION

This paper presents the results of a three part feasibility study into the use of environmental features as a basis for predicting the location of a body as it navigates through the environment.

The literature-based element highlighted features such as magnetic field anomalies and terrain height as possible features to bring forward into the next stage of the study.

The pedestrian experiment showed that certain features in the environment have temporal stability over a single day. These include magnetic anomalies which showed a variance of 3m in the position of the anomalous peaks detected over multiple rounds. Temperature showed correlation of the change in temperature within the rounds. Road signs showed an abundance of landmarks in the urban environment which is important as it assists in maintaining an accurate position fix.

The road experiment, which is the final phase of the feasibility study, expanded the number of sensors used and showed that multiple sensors could be used in different environments and that a particular feature could be more successful at providing a position in specific environments. For example, altitude sensors performed particularly well in undulating terrain but could not be used in the flat terrain found in the central London location of the pedestrian experiment. Also the use of road signs in an urban environment is advantageous because the generally lower speeds aid the recognition of signs which are abundant in this environment.

There was some promise seen in using temperature in specific environments although cross correlation values did not match those seen with altitude. Also of the two sensors used to assess road texture, the microphone showed more potential.

Using the two experimental stages of the feasibility study it was possible to evaluate the feasibility of the measurables included in the experiments. The features are ranked in Table 17 in order of feasibility.

**Table 17 – Measurables from experimental phase in order of feasibility**

| Feature | Sensor |
|---|---|
| Road Signs | Video camera |
| Terrain Height | Barometer |
| Magnetic Field | Magnetometer |
| Road Texture | Microphone |
| Temperature | Thermometer |
| Ambient Light | Light Sensor |
| Scent/Pollution | Air Quality Sensor |
| Road Texture | Accelerometer |
| Environmental Sound | Microphone |

This study has shown that it is possible to use environmental features to map a space and shown it should be possible to create a feature-mapping and navigation algorithm using a combination of environmental feature sensors, a GNSS receiver and sensors for dead reckoning.

## 6. FUTURE WORK

Further experiments and analysis will need to be completed on the remaining promising measurables from the literature-base study which have yet to be experimentally evaluated.

Following this will be the development of a feature-matching and navigation algorithm which incorporates inputs from the multiple sensors, a GNSS receiver and sensors for dead reckoning. The algorithm will run collecting sensor data while GNSS receiver data is available and store this in a database along with location stamps until called upon in times of GNSS receiver signal disturbance.

Upon completion of this algorithm a prototype containing the finalised environmental feature sensors, GNSS receiver and dead reckoning sensors will be created and tested in varying environments in order to optimise and assess the positioning algorithm.

In the long term, the environmental feature matching techniques proposed in this paper could form part of a new generation of multisensor integrated navigation systems alongside techniques such as GNSS shadow matching [11], low-cost array-based IMUs [33], opportunistic radio navigation [34] and context adaptivity [35].

**Acknowledgements**

Debbie Walter is jointly funded by Engineering and Physical Sciences Research Council (EPSRC) and Terrafix ltd.

The Authors would like to thank Kimon Voutsis for assisting in the pedestrian experiment and Henry Martin for his advice and assistance setting up the hardware for the road experiment.

**References**

1. Royal Academy of Engineering, "*Global Navigation Space Systems: Reliance and Vulnerabilities*," March 2011.
2. Groves, P. D., "*Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*," Second Edition, Artech House, 2013.
3. Hide, C., et al., *"Integrated GPS, LORAN-C and INS for Land Navigation Applications,"* ION GNSS, 2006.
4. Churchill, W., and Newman, P., *"Continually Improving Large Scale Long Term Visual Navigation of a Vehicle in Dynamic Urban Environments,"* IEEE Intelligent Transportation Systems Conference, 2012.
5. McManus, C., et al., *"Distraction Suppression for Vision-Based Pose Estimation at City Scales,"* IEEE Int. Conf. on Robotics and Automation, 2013.
6. David Nelson, editor, *"The Penguin Dictionary of Mathematics,"* Penguin, 3rd edition, 2003.
7. Shingu, H., *"An onboard measurement system of gravity gradients using inertial accelerometers,"* International IEEE Conference on Multisensor Fusion and Integration for Intelligent Systems, pages 108-115, 1996.
8. N. Yu and J.M. Kohel and J.R. Kellogg and L. Maleki, *"Development of an Atom-Interferometer Gravity Gradiometer for Gravity Measurement from Space,"* Applied Physics B, pages 647-652, 2006.
9. Jircitano, A., and Dosch, D.E., *"Gravity Aided Inertial Navigation System (GAINS),"* ION 47th AM, pages 221-229, 1991.
10. Canadian Micro Gravity. "*GT-2M marine gravimeter,"* Technical Specification, July 2013. URL: http://www.canadianmicrogravity.com.
11. Wang, L., Groves, P., Ziebart, M., *"Urban Positioning on a Smartphone: Real-time Shadow Matching Using GNSS and 3D City Models",* ION GNSS+, 2013.
12. Groves, P. D., *"Shadow Matching: A new GNSS Position Technique for Urban Canyons,"* Journal of Navigation, pages 417-430, 2011.
13. Vallivaara, I., Haverinen, J., Kemppainen, A., and Roning, J., *"Simultaneous localization and mapping using ambient magnetic field,"* International IEEE Conference on Multisensor Fusion and Integration for Intelligent Systems, pages 14-19, 2010.
14. Haiyang Zhang and Martin, F., *"Robotic mapping assisted by local magnetic field anomalies,"* IEEE Conference on Technologies for Practical Robot Applications, pages 25-30, 2011.
15. Judd, T. and Toan Vu, *"Use of a new pedometric dead reckoning module in GPS denied environments,"* IEEE/ION Position, Location and Navigation Symposium, pages 120-128, 2008.
16. Jeremiah Shockley and John Raquet,*"Three-axis magnetometer navigation in suburban areas,"* 25th International Technical Meeting of The Satellite Division of the Institute of Navigation, pages 1607-1618, 2012.
17. Kou Yi-min, Xie Wei-nan, Liu Rui, and Wang Chang-Hong, *"A geomagnetic positioning method with main magnetic field,"* 2nd International Symposium on Systems and Control in Aerospace and Astronautics, pages 1-4, 2008.
18. Kathrin Steck, Markus Knaden, and Bill S. Hansson, *"Do desert ants smell the scenery in stereo?,"* Animal Behaviour, 79:939-945, 2010.
19. National Geographic. *"Animal navigation,"* Website, May 2012. URL: http://education.nationalgeographic.com.
20. Shurmer, H.V., *"The fifth sense on the scent of the electronic nose,"* IEE Review, volume 36, pages 95-98, 1990.
21. Usman Zakir, Eran, Edirishinghe, A., and Amir Hussain, *"Road sign detection and recognition from video stream using HSV, contourlet transform and local energy based shape histogram,"* 5th International Conference on Advances in Brain Inspired Cognitive Systems, pages 411-419, 2012.
22. Gov.uk, *"Traffic signs,"* Website, August 2013. URL: https://www.gov.uk/traffic-signs
23. Wen Wu, Xilin Chen, and Lei Yang, *"Detection of text on road signs from video,"* 8th International IEEE Conference on Intelligent Transportation Systems, pages 378-390, 2005.
24. Günther Wyszecki and W. S. Stiles, W. S., *"Color Science: Concepts and Methods, Quantitative Data and Formulae,"* 2nd Edition, Wiley, 2013.
25. Digital Meters, *"Handheld digital thermometers,"* Website, May 2012. URL http://www.digital-meters.com
26. Soehren, W., and W., Hawkinson, *"A Prototype Personal Navigation System,"* IEEE/ION PLANS, pages 539–546, 2006.

27. Sönmez, T., and H. E. Bingöl, *"Modeling and Simulation of a Terrain Aided Inertial Navigation Algorithm for Land Vehicles,"* IEEE/ION PLANS, pages 1046-1052, 2008.
28. Pynn, J., Wright, A., and Lodge, R., *"Automatic identification of cracks in road surfaces,"* 7th International Conference on Image Processing and Its Applications, pages 671-675, 1999.
29. Mircea, M., Kovacs, I., Stoian, I., Marichescu, A., and Tepes-Bobescu, A., *"Strategic mapping of the ambient noise produced by road traffic, accordingly to European regulations,"* International IEEE Conference on Automation, Quality and Testing, Robotics, pages 321-326, 2008.
30. Microsoft Bing, *"Bing maps,"* Website, May 2012. URL: http://www.bing.com/maps/.
31. Ashok Ambadar, *"Analog and Digital Signal Processing,"* Brooks/Cole Publishing Company, 2nd edition, 1999.
32. Xsens, *"Xsens MTi-G,"* Website, May 2013. URL: http://www.xsens.com.
33. Martin, H., Groves, P., Newman, M., Faragher, R., *"A New Approach to Better Low-cost MEMS IMU Performance Using Sensor Arrays,"* ION GNSS+, 2013.
34. Webb, Toby A., Groves, Paul D., Mason, Robert J., Harrison, Joseph H., *"A New Differential Positioning Technique Applicable to Generic FDMA Signals of Opportunity,"* 24th International ION GNSS+, pages 3527-3538, 2011.
35. Paul D Groves, Henry Martin, Kimon Voutsis, Debbie Walter and Lei Wang, *"Context Detection, Categorization and Connectivity for Advanced Adaptive Integrated Navigation",* ION GNSS+, 2013.