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An Intelligent Navigation Solution for Land Mobile Location-Based Services

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The increasing availability of small, low-cost GPS receivers has established a firm growth in the production of Location-Based Services (LBS). LBS, such as in-car navigation systems, are not necessarily reliant on high accuracy but a continuous positioning service. When available, the accuracy provided by the standard positioning service (SPS) of 30 metres, 95% of the time is often acceptable. The reality is, however, that GPS does not work in all situations, and it is therefore common to integrate GPS with additional sensors. The use of low-cost inertial sensors alone during GPS signal outage is severely restricted due to the accumulation of errors that is inherent with such dead reckoning (DR) systems. Through the integration of spatial information with real-time positioning sensors, intelligence can be added to the land mobile navigation solution. The information contained within a Geographical Information System (GIS) provides additional observations that can be used to improve the navigation result. With this approach, the solution is not dependent on the performance capabilities of the navigation sensors alone. This enables the use of lower accuracy navigation devices, allowing low-cost systems to provide a sustained, viable navigation solution despite long-term GPS outages. Practical results are presented comparing solutions obtained from a hand-held GPS receiver to a gyroscope and odometer.

KEY WORDS

1. Integration. 2. Location Based Services. 3. GPS. 4. Dead Reckoning.

1. INTRODUCTION. The accuracies offered by the standard positioning service (SPS) of 30 metres, 95% of the time (AUSLIG, 2001) have been sufficient to generate a significant and increasing number of applications and users of Location-Based Services (LBS). Systems developed around the SPS only are unable to provide their users with a continuous navigation solution as buildings, trees, high vehicles and other obstructions can obscure the satellite signals. For many LBS, such as in-car navigation systems, a continuous navigation solution requires the integration of additional devices to bridge the periods of GPS outage. Typical integrations combine a GPS receiver with low-cost dead reckoning (DR) sensors such as gyroscopes and odometers. These systems, however, have an unbounded accumulation of errors over time, and their usefulness depends on the duration of GPS signal outage. Alternative integrations that use more expensive inertial sensors do improve the solution over longer durations of satellite outages but are often too costly for LBS.

To reduce the inaccuracies associated with low-cost inertial sensors over time, intelligent navigation can be applied. This is achieved through the integration of

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measurements provided by the navigation instruments with additional spatial information contained within a map database. Using the inherent intelligence of data contained in a Geographical Information System (GIS), data can be extracted and integrated into the navigation solution. This research shows that by integrating the intelligence of spatial information contained within a GIS, low-cost GPS receivers and DR sensors have a vital role to play in the design of intelligent navigation solutions.

2. INTELLIGENT NAVIGATION. Intelligent navigation is a process for improving the 'raw' navigation solution provided from low accuracy sensors by applying some of the simple rules of navigation that human beings follow on a day-to-day basis. When attempting to navigate to a specific location, a human navigator may perhaps wait for a recognisable street intersection in order to pinpoint the vehicle's location, and from this improve his estimate of absolute position. During normal driving situations, the navigator significantly narrows the search space when attempting to locate the vehicle's position by simply assuming it can only be on one of a fixed number of roads within a certain area, thereby constraining the solution. Using these simple rules and extending the concept to generate more complex rules, the accuracy of navigation systems can be improved and the accumulation of error in inertial devices significantly reduced.

In most real-time vehicle navigation systems, vehicle location is displayed on some form of digital map containing data useful to the driver. Since a GIS is an appropriate platform for efficiently storing and displaying feature and attribute information, it is a typical interface used in the design of intelligent navigation systems. Synonymous to the human navigator, information contained in the GIS can be used to generate a set of rules that releases the dependency of the system from the performance capabilities of the navigation sensors. In other words, spatial information can be used as an additional measurement or navigation instrument, not just a static digital map on which to display position.

3. DESIGN OF AN INTELLIGENT NAVIGATION SYSTEM. The intelligent navigation system developed during this research consisted of the following components:

(a) The navigation system integration host;
(b) The map database;
(c) The navigation sensors.

3.1. *The Navigation System Integration Host*. The navigation system integration host provides a platform to integrate the navigation sensors, analyse, adjust and display position. Although hardware integration can be achieved through the use of many commercially available programming environments (e.g. Microsoft Visual Basic™), the efficient and effective management, analysis and display of spatial data requires a customised GIS product. The GIS needs a capable programming language that can perform both spatial and non-spatial tasks swiftly and from which a user-friendly interface can also be built. For this project Smallworld GIS 3.1(0)™ was chosen. Smallworld's object-orientated language, Magik™, was able to communicate with Microsoft Visual Basic applications, enabling hardware integration to take place in Visual Basic, while the spatial analysis queries could be performed in the more

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Table 1. Definition of the RMC sentence components.

Sentence Component	Definition
RMC	Sentence code (Header)
101809	UTC time (hhmmss)
A	Receiver status: (A = navigation solution computed, V = unable to compute navigation solution)
3750.261	Latitude (ddmm · mmm)
S	Latitude is south (S) or north (N) of the equator
14503.808	Longitude (dddmm·mmm)
E	Longitude is east (E) or west (W) of Greenwich
000.0	Speed in knots
260.8	True heading in degrees
211299	UTC date (ddmmyy)
011.2	Magnetic variation in degrees
E	Magnetic variation is east (E) or west (W) of the meridian
*62	Checksum

suitable Smallworld Magik environment. Although Magik could have been used to integrate the hardware, the Microsoft Visual Basic programming language was chosen as it contains comprehensive serial communication functions that aided in communication with the navigation sensors.

3.2. *The Map Database*. Coordinates identifying the position of a vehicle hold very little value to the user unless they can be shown relative to recognisable map features such as road information. Digital map databases add value to the navigation solution by providing this sense of location. Furthermore, the spatial data can be integrated into the navigation solution.

For this project, the main source of data required was the road centre-line data for metropolitan Melbourne. The data was obtained in digital format from the responsible mapping agency in Victoria, Australia – Land Victoria. This spatial information was referenced to the Australian Geodetic Datum (AGD) and consisted of line features with text attributes. Each line feature represented the centre-line of a Melbourne metropolitan road and the text attribute provided the road's name. The data required conversion from the proprietary ArcInfo™ GIS export format to a format readable by Smallworld GIS. A software conversion product, Safe FME™ (Feature Manipulation Engine), was used for this purpose.

3.3. *GPS Hardware Integration*. Rapid developments in GPS receiver technologies have led to the design of smaller, more cost-effective electronics that has contributed to the growth of in-vehicle navigation systems. Small onboard receivers can provide regular updates of the vehicle's latitude, longitude and altitude. The interface between the GPS receiver and the processing software for this research was designed to be hardware independent so that different GPS receivers could be used. This is facilitated by the National Marine Electronics Association (NMEA) 0183 standards for data communication. The NMEA standard groups information into sentences.

For trials described in this paper, a Garmin GPS 45™ receiver was used. This receiver can track up to eight satellites simultaneously, supports the NMEA interface, and has an RS-232 serial communication output (Garmin International, 1994). The

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NMEA RMC sentence was used in the development of the navigation software. An example of this string is as follows:

RMC,101809,A,3750 · 261,S,14503 · 808,E,000 · 0,260 · 8,211299,011 · 2,E,*62

Table 1 describes the individual components of this sentence.

Using Microsoft Visual Basic, a conduit was developed to relay data from the GPS receiver to Smallworld GIS via an RS232 serial communications port. The conduit also parsed the data, ensuring only information from RMC fields were extracted and passed on. A graphical user interface (GUI) was produced in Smallworld Magik to display the GPS information received. Using the graphical capabilities of the GIS, the position of the receiver could be displayed in real-time with reference to the mapbase. In order to display the location of the receiver in the correct datum, the coordinates provided by the GPS were transformed from WGS-84 to the AGD and converted into Australian map grid coordinates.

Additional features of the real-time satellite navigation application include:

(a) Ability to draw the location of the receiver in real-time, or only once the GPS receiver has moved more than a specified distance;
(b) Option to log the receiver's position;
(c) Loading previously logged receiver positions for later viewing and analysis;
(d) Capability to store user preferences for each user of the system, such as automatic logging to a previously specified file and plotting positions at previously specified intervals;
(e) Drawing the location in a user-selected symbol, including pointing the symbol in the direction of movement;
(f) Displaying times and dates for different time zones.

3.4. *DR Hardware Integration.* With the importance placed on GPS for navigation, 'it is easy to forget that for many years the principal means of navigation was inertial navigation' (Heij, 1999). Parallel developments in DR and inertial technologies have led to improvements in the cost and performance of these sensors. However, the potential of navigation with DR is still limited by inaccuracies that are introduced into the measurements of direction and distance over time. In terms of direction, gyroscopic drift is of particular concern. Gyroscopic drift causes the gyroscope to indicate a change in direction has occurred, even though the instrument may be stationary. Typically, however, the largest error source is introduced during distance measurement.

Often distance measurement is dependent on the vehicle's wheel rotation rate. This measurement is a function of several factors including tyre radius, temperature, pressure and tread as well as road conditions (Madhukar *et al.*, 1999). Many of these conditions are likely to change even over short periods of time, and therefore introduce errors that are at best difficult to compensate for.

The DR system designed for this project comprises a fibre optic gyroscope (FOG) as the navigation device for use instead of the GPS receiver. The FOG has an RS-232 serial communication output at 9600 baud and is capable of measuring a maximum rotation rate of plus or minus 100 degrees per second (KVH Industries, Inc., 1999). The FOG is able to determine changes in direction and so can compute a relative bearing based on an initial bearing. However, DR requires not only bearing, but also distance. In order to compute distance travelled, the FOG must be attached to the vehicle's electronic control module (ECM). The ECM provides pulses

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proportional to the speed of the vehicle, and hence proportional to the distance travelled. Similar to the GPS receiver, the FOG's output is via an RS-232 serial interface; however, rather than ASCII (text) output, the FOG's output was encoded in a 64-bit binary string. In addition to the GPS receiver conduit, another conduit was written in Visual Basic to decode the binary data before passing it on to the GIS. The following information could be extracted from the FOG:

(a) Rotation rate;
(b) Count of distance pulses from the ECM;
(c) FOG temperature;
(d) Gyroscope serial number;
(e) Checksum.

From the information provided through this conduit, additional algorithms converted the gyroscope rotation rate into a relative bearing and the count of distance pulses from the ECM into a distance measurement. This data was sufficient to calculate change in easting and northing from the last known position to the current position.

For this conduit and related algorithms to operate accurately, some constants needed to be defined in order to convert from rotation rate to degrees per second and ECM pulse to distance measurement. While the manufacturer of the FOG supplied the rotation rate to degrees per second conversion constant, the ECM pulse to distance measurement can vary depending on car specifications such as wheel size and ECM settings. The value of this constant was therefore calculated through calibration by driving a known distance several times while recording the number of ECM pulses.

Additionally, the value of the zero offset bias (drift) must also be known when using FOG output for navigation. The zero offset bias is the rate of drift that the gyroscope exhibits when actually stationary. This constant can be calculated by recording stationary results over a known period of time and then applying an appropriate bias to each measurement to reduce the drift to zero. Since this constant is reliant on FOG temperature, it needs to be updated as the temperature changes. The FOG could then be integrated into the GIS and its output used for navigation.

The fundamental difference between navigation by satellite and DR is that each satellite receiver measurement epoch provides a solution that is (for the purpose of navigation) independent from the last epoch. On the other hand, DR depends on the previous location in order to calculate the next location. Hence, for navigation using the FOG, the user is first required to input a starting location and initial direction. These initial values can be set by allowing the user to place two points on the mapbase. The first point indicates the current position, and the direction from the first to the second point is the direction of travel. Alternatively, these values can also be entered via the keyboard. All the additional features of the real-time GPS navigation application are also available during FOG navigation.

4. TESTING OF THE NAVIGATION SYSTEM WITHOUT INTELLIGENT NAVIGATION.

In order to test the functionality of the GPS and DR Navigators, a test circuit was established in the suburbs of Melbourne. The circuit was 5090 metres long and contained areas of dense road network. The test's purpose determined if the system could detect which road the vehicle was on, even though the distance between some parallel roads was as little as 40 metres. If an error in absolute

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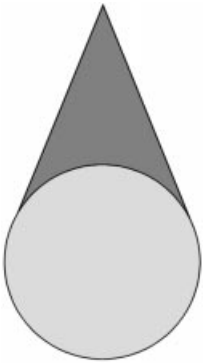


Figure 1. Position icon: it points in the direction of movement.

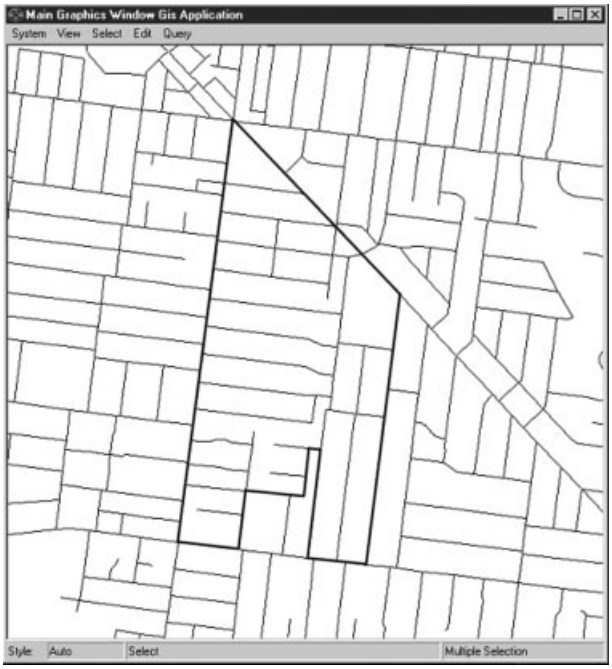


Figure 2. The test circuit (shown in bold).

position of over 20 metres occurred, this would be sufficient to place the vehicle on or nearer to roads other than the road it was travelling on. The position of the vehicle was displayed in the GIS by the icon shown in figure 1. The arrow of the icon points in the direction of the vehicle's movement.

Figure 2 shows a plot of the test circuit established for this project. The aim of this test circuit was not to test the limitations of the equipment due to external factors, such as signal blockage, and therefore did not contain features that would significantly contribute to these problems. The circuit was sufficient in length to assess the effect of error accumulation.

Figure 3 shows the results obtained when the test circuit was travelled with the GPS receiver calculating and plotting results in real time. The sometimes erratic

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Figure 3. GPS navigation without intelligent navigation.

appearance of these results demonstrates that even though the vehicle was on the circuit at all times, general inaccuracies of the receiver caused the navigation path to appear off track. However, the test proved the functionality of the navigation system using a satellite navigation system receiver as its navigation device.

The DR Navigator application was also proved on the test circuit (Figure 4). The results demonstrated that the solution suffered from accumulation of errors over time. However, over short periods of time, the FOG provides more accurate results for relative positions and, compared to the GPS Navigator, the positions were less erratic between epochs.

5. INTEGRATING INTELLIGENT NAVIGATION.

This research indicated four practical rules that could be implemented to improve navigation using information from a mapbase:

(a) closest road;
(b) bearing matching;
(c) access only;
(d) distance in direction.

5.1. *Closest Road.* One step towards intelligent navigation is to make the assumption that a land vehicle travels on roads. The constraint operates by using the satellite or DR estimated position of the vehicle and the GIS mapbase to locate the closest road. The closest point on the closest road can be identified and the location of the vehicle adjusted to this point. The result of this constraint for satellite navigation is shown in Figure 5 and for DR navigation in Figure 6. For the DR

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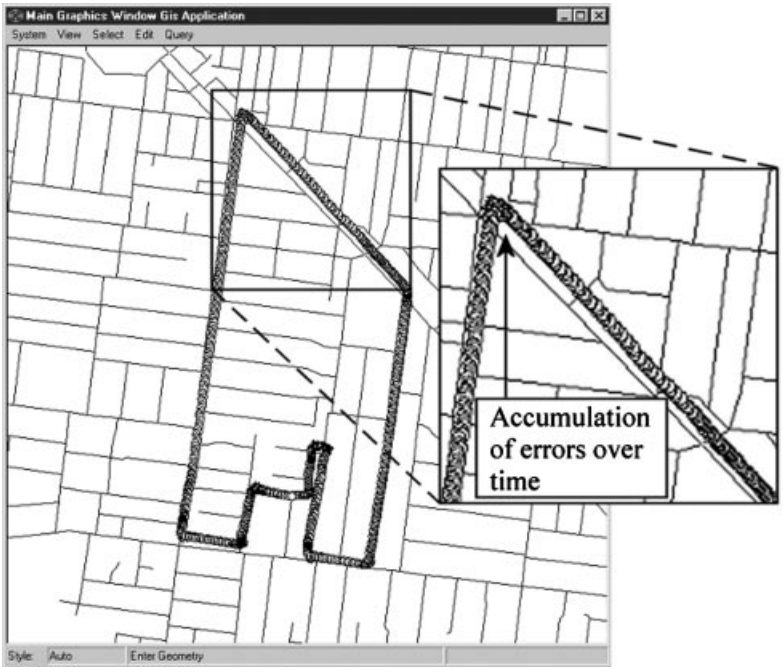


Figure 4. DR navigation without intelligent navigation.

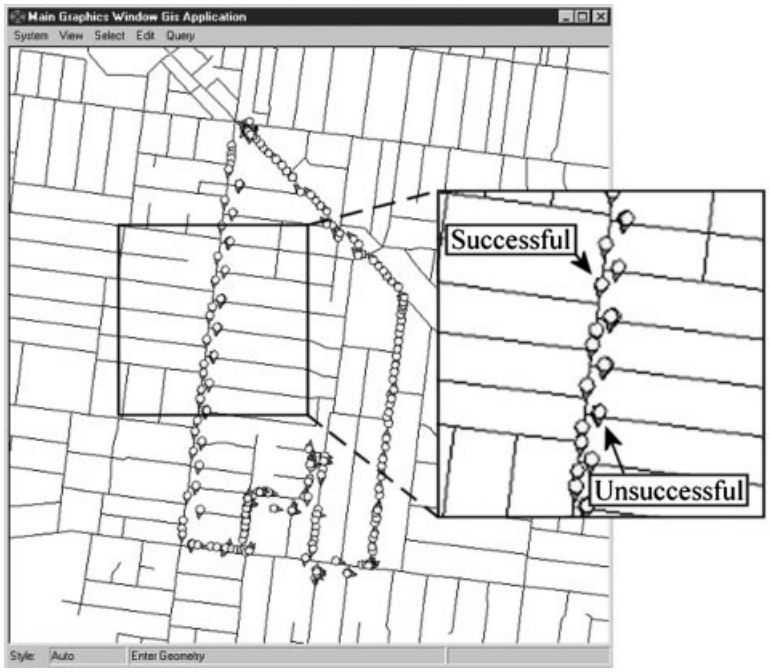


Figure 5. Satellite navigation with closest road constraint.

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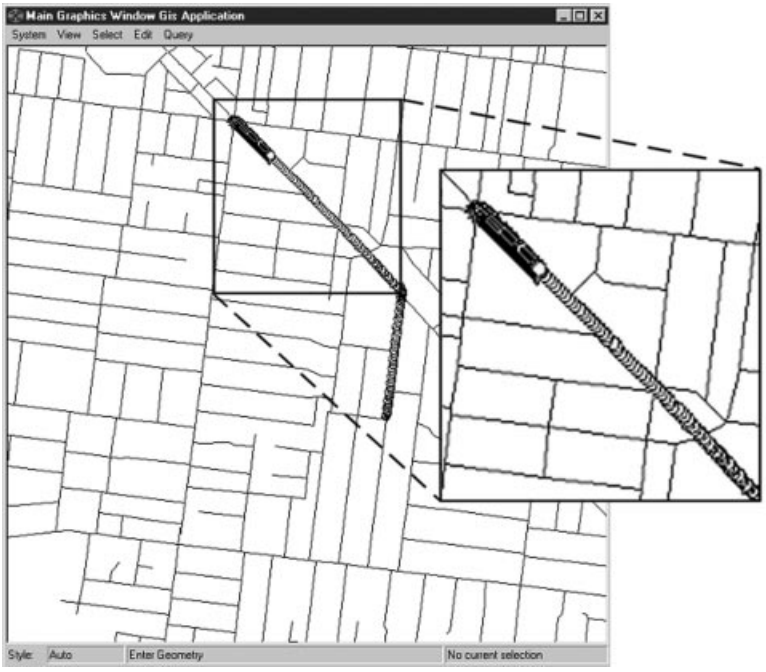


Figure 6. DR navigation with closest road constraint.

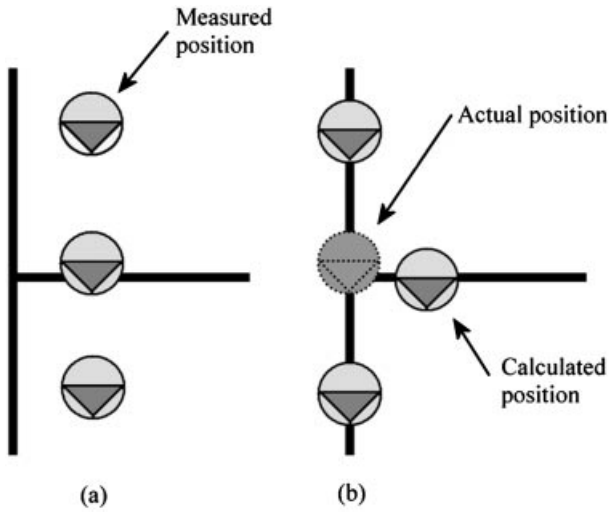


Figure 7. Closest road constraint: (a) navigation without correction, and (b) navigation with correction.

navigation system, the solution of the current location is based on the corrected position (i.e. the closest road point) of the last estimated position.

For the satellite navigator, this simple algorithm was effective when the uncorrected position placed the vehicle closer to the road the vehicle was on, compared to other

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roads in the area. However, when approaching intersections or when roads were closely spaced, errors in the raw GPS position often located the vehicle on incorrect roads. In brief, when the error in the satellite receiver position is greater than half the distance to the road actually being travelled on and other roads in the vicinity, the algorithm may choose the incorrect road and downgrade rather than improve the position solution. Figure 7 demonstrates the occurrence of this situation.

For the DR navigator, the algorithm functions effectively until the vehicle turns a corner at a time when error in distance measurement has accumulated. At this point, the errors may cause the vehicle's estimated position to be short of or passed the intersection. Additional corrections using the closest road rule continually position the vehicle back on the road of origin prior to the vehicle turning the corner. Figure 8 illustrates this error.

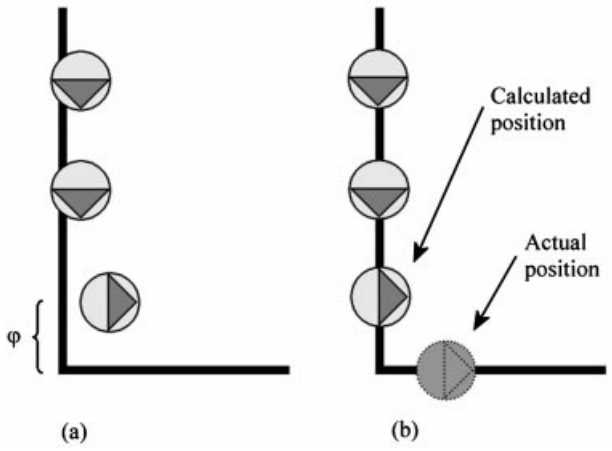


Figure 8. Correcting to the nearest road with accumulated distance error φ: (a) navigation without correction, and (b) navigation with correction.

5.2. *Bearing Matching*. The previous tests demonstrated that the closest road constraint has difficulty improving the navigation solution when roads are closely spaced, particularly at road intersections. An additional constraint that examines road direction is also required. When searching for the nearest road, the heading of the road should also be approximately the same as that of the moving vehicle. If such a road could not be found, then the solution defaults to the uncorrected position until a road matching both constraints can be identified.

The results of these constraints are shown in Figures 9 and 10 for satellite navigation and DR navigation respectively. This additional constraint significantly improves the navigation solution. The largest source of error in this solution occurs when turning a corner and is particularly obvious in Figure 9. As the vehicle turns a corner, there is a stage where neither the road it is turning from or to match the vehicle orientation. Hence, the position of the vehicle is plotted without correction. If there happens to be a road within the vicinity that coincidentally matches a direction in between that of the roads being turned from and to, then the location jumps to that position. In the situation where roads are close together and have the

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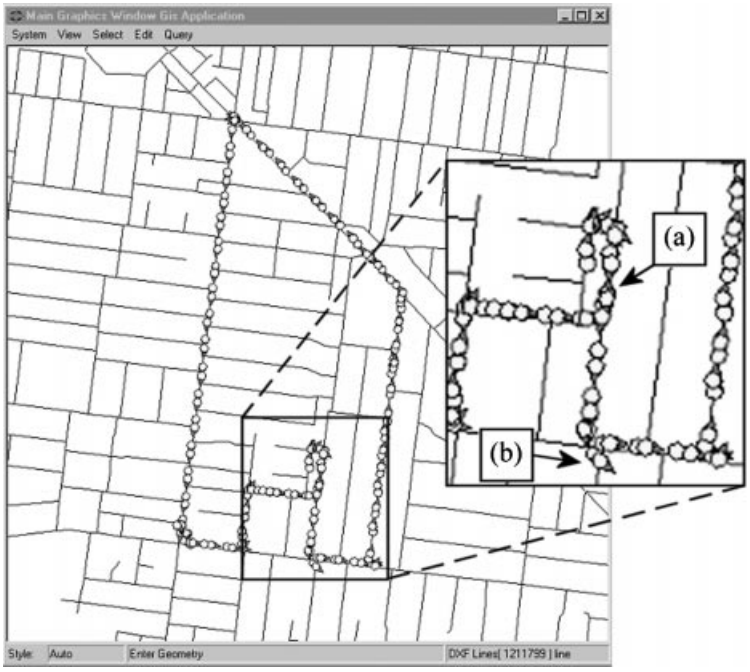


Figure 9. Satellite navigation with bearing matching constraint: (a) two close roads with similar bearings cause an error in the corrected position estimation, and (b) when turning a corner, no road matches the vehicle bearing and an uncorrected position is plotted.



Figure 10. DR navigation with bearing matching constraint.

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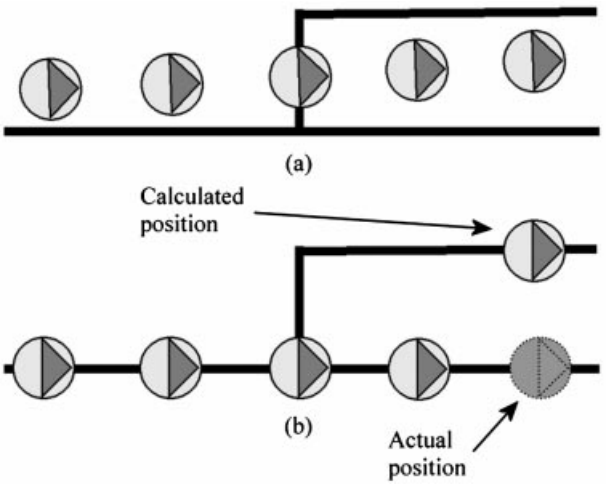


Figure 11. Correcting to the nearest road taking road bearing into account: (a) navigation without correction, and (b) navigation with correction.

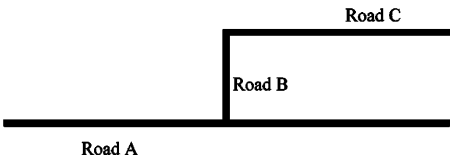


Figure 12. Road layout scenario.

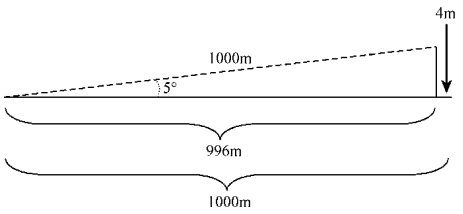


Figure 13. Distance error propagated from bearing measurement error.

same bearing, difficulty is still encountered when choosing the correct road. Figure 11 demonstrates this error.

The DR navigation system is able to use the road direction constraint to reduce errors that have accumulated in both distance and direction. For instance, when the vehicle turns a corner, the road direction constraint corrects the vehicle position to that of the new road, thereby eliminating the accumulated distance error. The more frequently the vehicle turns corners, the more often accumulated errors are removed. However, if the vehicle is travelling in a particular direction for a long duration, the accumulated distance error may become so large that the vehicle's estimated position and therefore the corner identified in the database that the vehicle has turned could be in error. Without the ability to position itself absolutely, DR must then rely on the user to reset its true position.

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5.3. *Access only*. In situations where two roads with the same orientation are close together (Figures 9(a) and 11), it may be difficult to determine upon which road the vehicle is travelling. The access only constraint helps resolve this situation by determining if the road could have been accessed. Approaching the situation logically can solve the error described in Figure 11. Take, for example, the road layout as shown in Figure 12.

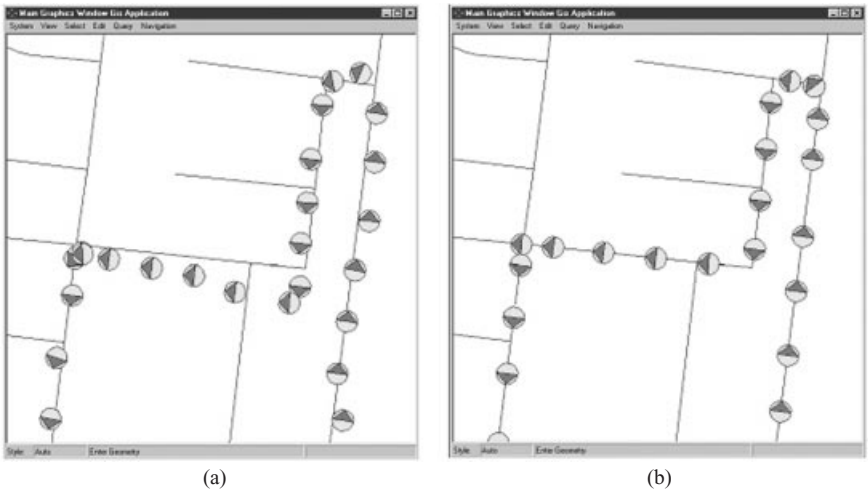
Assume a vehicle travelling along road A. If the only route to road C is via road B, then for the vehicle to be travelling along road C, it must previously have travelled along road B. By applying a short-term memory of previously travelled roads, the navigation system no longer introduces navigation errors such as those shown in Figure 11.

5.4. *Distance in direction*. This final rule further reduces the accumulation of distance error by calculating the distance travelled by the vehicle in the direction of the road rather than the direction measured by the navigation device. This is particularly important when navigation instruments of low accuracy are employed. For example, if the vehicle travels 1000 metres along a road of bearing 060 degrees while measuring the road to have a bearing of 065 degrees (i.e. 5 degrees in error), then an error in distance of 4 metres would occur (Figure 13).

Although this may seem insignificant, over several kilometres, or with lower accuracy navigation instruments, large errors can accumulate. For example, a bearing error of 15 degrees over 1 kilometre can result in a 35-metre error in distance. This error is avoided by calculating the distance travelled independently from the bearing of the vehicle and then applying this distance in the direction of the road being travelled along.

6. TESTING OF THE NAVIGATION SYSTEM WITH INTELLIGENT NAVIGATION.

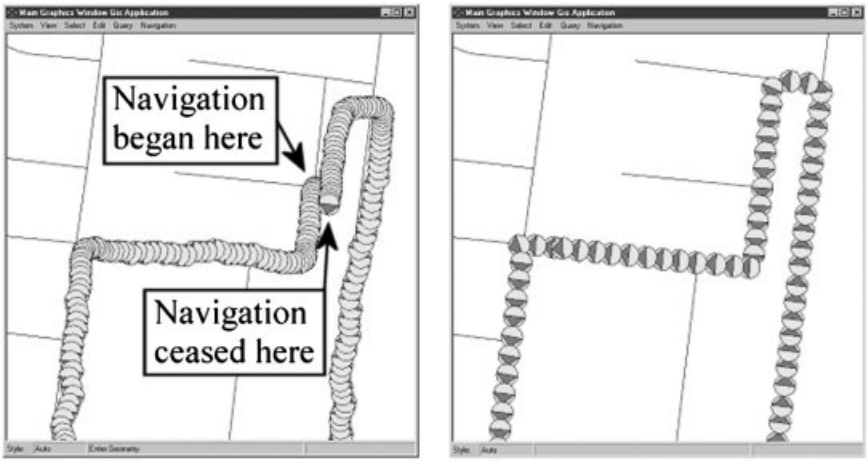
The combined intelligent navigation constraints were tested when travelling the circuit previously described. The different navigation systems of satellite and DR were tested independently. Figures 14(b) and 15(b) show



(a) (b)

Figure 14. (a) Satellite navigation without intelligent navigation, and (b) Satellite navigation with intelligent navigation.

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(a) (b)

Figure 15. (a) DR navigation without intelligent navigation, and (b) DR navigation with intelligent navigation.

the results of intelligent navigation on a small part of the test circuit. For comparison, Figures 14(a) and 15(a) show the same part of the test circuit travelled without intelligent navigation. The section of circuit shown in these figures is approximately 1 kilometre in length. Due to the fast data capture rate of the FOG, in order to show clearly the vehicle location in Figure 15(b), an option of the navigation system was used to display vehicle position only at a specified interval.

In all cases, intelligent navigation was able to provide significantly improved results. Figure 15(a) clearly shows the accumulation of error in DR navigation. The start and end point of navigation were, in fact, geographically the same. However, accumulated error of 20 metres over 1 kilometre had affected the navigation result. Using intelligent navigation, the error was reduced to 8 metres – an improvement of more than 50%. Continued navigation around the test circuit increased the accumulated error in the DR navigation system by approximately 2% of the distance travelled, or around 100 metres for each circuit or 500 metres after 5 circuits. Intelligent navigation was able to reduce this error on all parts of the circuit for every lap of the circuit to no more than 2% of the longest straight section, or around 30 metres or better during all times.

The most significant impact of intelligent navigation is upon DR navigation. While over the short term the amount of error correction required does not appear significant, over longer periods of time intelligent navigation largely reduces the accumulation of errors to which DR navigation is prone. This enables sustained navigation in DR mode without requiring frequent input from absolute positioning devices. This factor is important for navigation within the urban environment where urban canyoning could otherwise be a problem.

7. ERROR CAPABILITY TESTING.

An important aim of intelligent navigation was to reduce the accuracy requirements of the navigation devices, thereby reducing the cost of navigation systems. The GPS equipment used in the project was a low-cost 8-channel GPS receiver, while the standard vehicle odometer was employed for distance measurement. However, an alternative device to the relatively

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costly FOG would enable a further reduction in the total system cost. Alternative devices could include a low-cost digital magnetic compass or low-cost microelectro mechanical system (MEMS) gyroscope.

In order to test the ability of the navigation system to cope with a lower accuracy device, error was deliberately introduced into the bearing measurement of the FOG. A random error of plus or minus 30 degrees was added, thus allowing for a 60 degree window of error (Figure 16). This configuration was used around the test circuit.

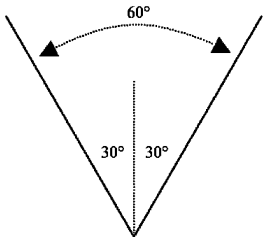
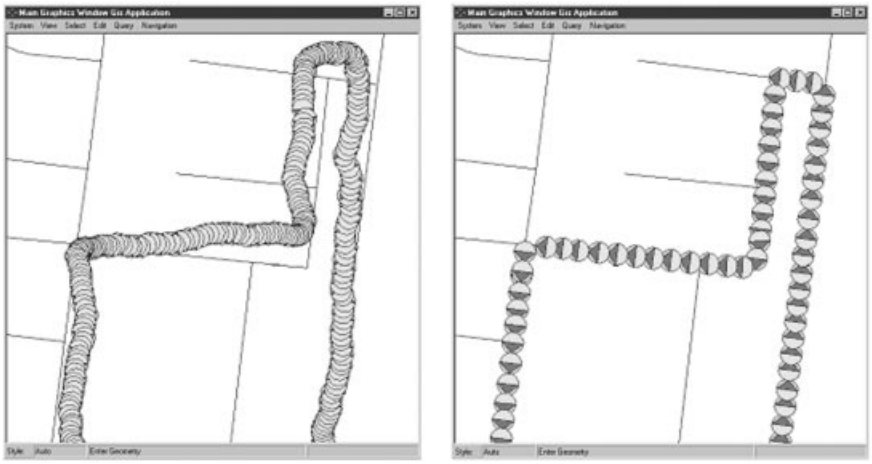


Figure 16. 60° window of error.

Figure 17(a) shows the results of introducing the 60-degree window of error (when travelling the same section of the urban test circuit as in Figures 14 and 15) with intelligent navigation switched off. Figure 17(b) shows the result with intelligent navigation switched on.

Intelligent navigation was able to compensate for these errors of up to plus or minus 30 degrees. It is important to note however, that all roads in this area of the circuit intersected at approximately 90 degrees. If roads were to intersect at around 60 degrees, errors in bearing of 30 degrees occurring at such intersections may be sufficient to affect the navigation solution terminally. This indeed was the case in other areas of the test circuit where road intersections of less than 60 degrees in angle occurred. However, with a high degree of error such as this within the system, limitations must be expected. Robust integration with other navigation devices (such as GPS) would enable errors to be avoided or recovered from.



(a) (b)

Figure 17. (a) DR navigation without intelligent navigation and random error of $\pm 30°$, and (b) DR navigation with intelligent navigation and random error of $\pm 30°$.

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8. CONCLUSION. Integration of GPS measurements and DR information through a Kalman filter has been common practice for some time. The absolute positioning advantages of GPS combined with the self-contained solution of DR enables a navigation system that can operate in a range of environments. In ideal situations, the relative stability of DR devices helps to enhance the navigation solution; however, in more challenging environments where GPS signals are obstructed, DR quickly succumbs to the accumulation of errors.

This research demonstrates that the integration of spatial information into the navigation solution can significantly improve navigation results, and prolong successful navigation in areas where absolute positioning is unavailable. Although not traditionally recognised as a navigation instrument, input from spatial data can provide vital navigation measurements. To realise the potential of navigation systems fully, measurements from spatial data should also be included in the filtering process.

The advantages of spatial data integration would be particularly beneficial to LBS, where low-cost navigation devices are used. The inclusion of measurements from spatial data would not require additional devices or data (as almost all LBS use a digital mapbase to provide users with a sense of location), but such inclusion could significantly improve operation in the challenging urban environments.

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