Intelligent Navigation, Inertial Integration

Double Assistance for GPS

May 1, 2002
By: Paul Cross, Allison Kealy, Stephen Scott-Young, Frank Leahy
GPS World

E-mail This Page

Pages | 1 | 2 | 3 more

Location-based services (LBS) delivered through in-car navigation systems and wireless handheld devices do not necessarily require highly accurate position information. They do require a continuous solution linked to spatial data, providing location-specific information. Systems developed around GPS alone cannot provide continuous position updates when buildings, trees, or passing vehicles obscure satellite signals. Integrating multiple sensors can enable a continuous navigation solution.

However, typical integrations combining a GPS receiver with low-cost dead reckoning (DR) sensors such as magnetic compasses, gyroscopes, and odometers cannot contain the accumulation of errors over time - most significantly, over the time that GPS signals may be unavailable. Using more expensive inertial sensors improves the solution over longer outage periods, but costs too much for typical LBS.

Intelligent navigation can reduce inaccuracies associated with low-cost inertial sensors over time. This process integrates measurements provided by the navigation instruments with additional spatial information contained within a map database and interrogated by a geographical information system (GIS).

We investigated the potential of MEMS sensors to form a standard integration component with GPS, developing the next generation of

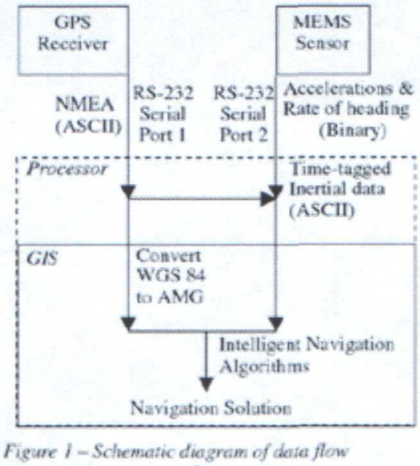


Figure 1 Data flow between the navigation instruments and the GIS

positioning sensors for low accuracy (LBS) applications, and we present here a simple solution further integrating the measurements from such a configuration with spatial information already linked to LBS . This type of integration offers improved accuracy and performance of low cost, low precision sensors.

Microelectro-mechanical systems (MEMS) technology enables a tighter, more compact integration of sensors with a complete inertial navigation system on a single microelectronic chip. The micromachining process used to construct MEMS technology provides a significant reduction in size and supports bulk manufacturing, an important component of cost reduction.

A simple navigation unit consisting of a GPS receiver, a MEMS gyroscope, a MEMS accelerometer, and incorporating accurate map data achieves several advantages:

- All measurements required for navigation are independent of the vehicle. Distance travelled and change in heading can be calculated from the accelerometer and gyroscope respectively, rather than from the vehicle's odometer and wheel sensors. This constitutes an advantage, particularly for aftermarket suppliers, as self-contained systems are easier to install.
- All navigation instruments can be manufactured in bulk, providing a low cost system.
- Since the system relies on both radiolocation and DR, a continuous navigation solution is available despite the blockage of GPS signals in areas such as urban canyons.

System Design

The components in our prototype system represent commercially-available products in MEMS, GPS, and GIS technology. Figure 1 shows the connection and data flow between them. To test system capabilities within a typical application, we fitted the components to a land vehicle as part of an in-car navigation system.

A base station recorded dual-frequency carrier phase observations to quantify the effectiveness of the intelligent navigation solution.

An inertial sensor provided relative measurements of heading and distance for the vehicle. To simulate a low-cost MEMS sensor, we extracted only direct measurements from the gyroscope yaw axis and the accelerometer x-axis of a larger, more expensive sensor consisting of three MEMS accelerometers, three MEMS gyroscopes, three magnetometers, and a temperature sensor. The unit provides digital output via an RS-232 port at a maximum output rate of 75 measurements per second.

While we set out to demonstrate the performance capabilities of a low-cost GPS receiver in this configuration, to quantify improvements in performance we used a higher-grade dual frequency receiver system, operating it in two modes. The absolute GPS position computed by a single receiver functioned as the input to the intelligent navigation system. At the same time, we also recorded dual frequency carrier-phase observations with a nearby base station, to enable kinematic-on-the-fly (KOF) post-processing of these differential measurements. This determined the position of the moving vehicle to an accuracy of 1-3 centimeters. By comparing these position solutions with those of the intelligent navigation system, we could accurately quantify the effectiveness of the solution.

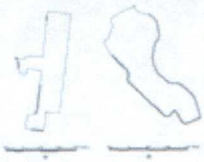


Figure 2 Test circuits near (a) University of Melbourne and (b) Melbourne Formula One Grand Prix Track showing the locations (circles) where KOF solutions could be computed

The absolute GPS position was derived from the NMEA output string obtained every one second from the GPS system. The GPS time from the NMEA output time-tagged the data obtained from the inertial system.

We mounted the inertial sensor on a wooden platform fixed to the test vehicle, aligning it in the direction of travel of the vehicle and parallel to the vehicle. The GPS antenna was mounted on the roof, and an on-board computer facilitated the recording and the time tagging of the data, as well as implementation of the intelligent navigation algorithms. The computer also formed the platform for serving the digital map data from within the GIS software.

MEMS Performance

Prior to testing the complete intelligent navigation system, we tested the MEMS sensors themselves to assess their performance in both static and dynamic senses. The 40-minute static tests demonstrated reasonable gyroscope and accelerometer stability.

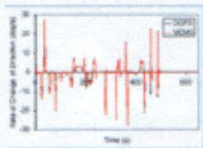


Table 1 & Figure 3

We first intended to conduct dynamic tests on roads near the University of Melbourne campus. These roads provided a typical urban environment with significant roadside infrastructure. We needed to compare the intelligent navigation solution with the true vehicle trajectory. However, as the true trajectory was to be computed using KOF techniques, we quickly realized that the frequent blockage of GPS signals and the need for ambiguity resolution in the KOF solution meant that very few high accuracy vehicle positions (and consequently velocities and accelerations) could be determined on campus.

Therefore we tested the inertial sensors on a 5,320-meter circuit of the Melbourne Formula One Grand Prix racetrack. Figure 2 shows the locations where KOF solutions could be computed for both the original test area near the University of Melbourne, and the Formula Grand Prix track.

Home | Past Issues | Subscribe

September 4, 2002

SEARCH
Whole Site
Advanced Search

The Magazine
GPS World
Media Kit
Subscribe
Contact
Staff / Advisors
Services
From The Editor
GPS News
Global View
GPS Inside
Washington View
Industry View
Calendar
GPS Jobs
GPS Reference
Galileo's World
GPS Products
Receiver Tech
Nav & Guidance
Survey & Map
Tracking/Wireless
Timing
Military
Related Hardware
Software
Buyers Guide
LeadNet

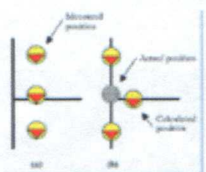
Intelligent Navigation, Inertial Integration

Double Assistance for GPS

May 1, 2002
By: Paul Cross, Allison Kealy, Stephen Scott-Young, Frank Leahy
GPS World

E-mail This Page

back | Pages | 1 | 2 | 3 more



Figures 4 - 6

Table 1 and Figure 3 show the results obtained from comparing the rate of change of direction from the inertial sensor MEMS gyroscope with those derived from the GPS post-processed positions. The average difference between the MEMS and GPS rate of change in direction was 20.014 degrees/second and a standard deviation of 1.711 degrees/second. These results are considerably larger than those found during the static testing, demonstrating that in a dynamic environment, the gyroscope is less stable.

We obtained similar results for the accelerations measured by the inertial sensor and those derived from the GPS in the direction of travel, and for the derived velocities from the inertial sensors and the GPS measurements.

We also compared the accelerations measured by the inertial sensor with those derived from the GPS in the direction of travel, and the derived velocities from the inertial sensors with the GPS measurements. We found similar results as with the gyroscope, indicating that the accelerometer is less stable in a dynamic environment. For the derived velocity, the propagation of error from the accelerometer measurements over time was clearly evident. This also accounted for a drift in the derived MEMS velocities.

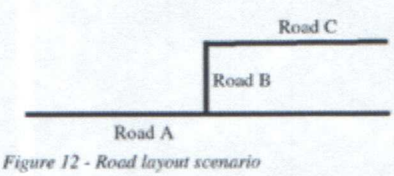


Figure 7 Road layout scenario

Errors Accumulate. While the accelerometer and differential carrier-phase GPS results compare favorably, it is evident that over time, errors accumulate in the accelerometer-derived velocity measurements. The successful use of these MEMS navigation instruments over several minutes would be severely limited if drift and noise could not be significantly reduced.

To navigate with DR techniques, navigation sensors must provide enough information to derive heading and distance measurements. In the case of the MEMS gyroscope and MEMS accelerometer, these observations are not directly measured, however they can be derived. As the gyroscope can record angular rate of change, with prior knowledge of an initial heading from the GPS receiver, then adding the average rate of change measured between epochs, the updated heading can be calculated. Similarly, distance can also be calculated from the MEMS accelerometer.

By knowing the initial speed of the vehicle (either from the GPS receiver, or if the vehicle was stationary) and adding the average acceleration measured between epochs, an updated estimate of velocity can be maintained. Distance can be calculated as a function of velocity and time. Of course, measurements sampled from the gyroscope and accelerometer must occur at a sufficiently fast rate to minimize the accumulation of errors due to unrecorded changes in direction and acceleration.

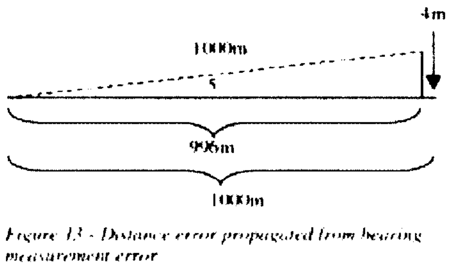


Figure 8 Distance error propagated from bearing measurement error

The large standard deviations for the gyroscope and accelerometer measurements indicate that the measurements themselves have low precision, and any parameter derived from an accumulation of these measurements over time would deviate significantly from its true value in a very short time period. The use of absolute-position GPS measurements such as those received in the NMEA output in this navigation system can help reduce the accumulation of errors in the DR navigation system. Intelligent navigation can also help reduce error accumulation and improve the navigation solution. Furthermore, intelligent navigation can operate where GPS signals and GPS measurements are unavailable.

Intelligent Navigation

Intelligent navigation improves the basic solution obtained from low-cost navigation sensors for land mobile applications through integration of measurements from the navigation instruments with additional spatial information contained within a map database.

The four principal rules of intelligent navigation identified in this research are:

- access only
- bearing matching
- closest road
- distance in direction

Closest Road. The first step towards intelligent navigation assumes that the vehicle is travelling along a road - typically the case. The location solution can include this constraint, improving the accuracy of the computed position of the vehicle.

This simple algorithm is effective when the nearest road is in fact the road being travelled. However, when approaching intersections or when two roads are close to each other, the nearest road may not be the road being travelled. In these situations, searching for the nearest road downgrades the position solution (Figure 4).

Additional errors in DR navigation may arise, as when the vehicle turns a corner. Due to accumulation of distance errors, when turning a corner, the nearest road can still be the previous road of travel (Figure 5). Without the ability to determine absolute position, further DR navigation becomes increasingly erroneous.

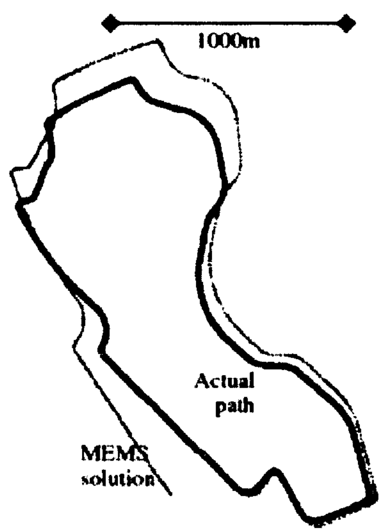


Figure 9 Accumulation of error using MEMS sensors (black line). Blue shows the actual track travelled, and yellow dots show position as reported by intelligent navigation. Intelligent navigation corrects vehicle position to the most likely trajectory, and hence a plot of the corrected results (yellow dots), always seems to show a perfect solution: the vehicle position is always on the track. However, while the intelligent navigation rules correct the position back to the estimated trajectory,

Bearing Matching. Clearly, as the closest road rule takes into account only absolute position and not vehicle bearing, it alone is not sufficient. Bearing matching requires that the nearest road to which the vehicle's position is corrected must have a similar bearing to the direction of travel. This corrects the problems previously described. The threshold of similarity between the vehicle's bearing and the bearing of the surrounding roads may be adjusted to suit the accuracy of the navigation instruments. However, the larger the threshold, the more likely roads will be incorrectly matched as having the same bearing as that of the vehicle.

errors occurring along the line of the trajectory are more difficult to eliminate. These errors, which can rarely be identified from a position plot, are evident in Table 2 as they contribute to the RMS error of the MEMS with intelligent navigation. Accumulation of these types of errors is particularly a problem on long, straight roads. However, the more often the vehicle turns a corner, the more often this error can be eliminated (see Figure 5).

The significance of this rule must not be overlooked when navigating using DR. Typically, the largest error source is introduced from distance measurements. The combination of the closest road and bearing matching rules adjusts for this error each time the vehicle changes bearing above the threshold amount. For instance, the distance error w, shown in Figure 5, is removed by intelligent navigation. The more often the vehicle turns a corner, the more frequently accumulated distance error is eliminated.

Access Only. Figure 6 shows a case where application of the closest road and bearing matching rules incorrectly positions the vehicle. The access only rule is designed to identify and prevent this error from occurring.

Roof-mounted GPS antenna on vehicle

TABLE 2 Navigation error using the MEMS sensor during one circuit of the track

Navigation Mode	RMS error (m)	Standard deviation (m)
MEMS	96	63
MEMS with Intelligent Navigation	37	20

Take, for example, a vehicle travelling along road A in Figure 7. Assuming the only route to road C is via road B, logic dictates that for the vehicle to be travelling along road C it must previously have travelled along road B. By logging previously travelled roads, the navigation system can prevent the vehicle from being located on a road where it could not possibly be.

Distance in direction. This final rule further reduces 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 using low-accuracy navigation instruments. For example, if a vehicle travels 1,000 meters along a road of bearing 60 degrees while measuring the road to have a bearing of 65 degrees (that is, 5 degrees in error), an error in distance of 4 meters will occur (Figure 8). Although this may seem insignificant, larger errors can accumulate over several kilometers, or with lower-accuracy navigation instruments. Calculating the distance travelled independently from the bearing of the vehicle and then applying this distance in the direction of the road being travelled avoids this error.

Implementing the Rules

We programmed the four rules of intelligent navigation into the navigation system. The fundamental requirement of the algorithm is the ability to search for roads (defined by centerlines in the GIS database) in the vehicle's vicinity (as determined by the navigation instruments). The navigation system can then interrogate these road centerlines for information such as distance to the uncorrected navigation solution and centerline bearing. It then applies the intelligent navigation rules to correct the position solution. If more than one road segment matches all intelligent navigation constraints, the system selects the closest solution.

The most advantageous method of combining DR(MEMS), GPS, and intelligent navigation to produce a single navigation result appears to be the incorporation of intelligent navigation into a Kalman filter. We are still developing this process. For this project, we adopted only a simple process of measurement combination. Essentially, when navigating using combined navigation instruments, the system uses GPS measurements as the primary navigation solution, applying DR solutions only when a GPS solution is not available. During satellite signal outages, the system uses the last known position, vehicle velocity, and vehicle heading to continue the DR navigation solution.

Performance. We again used the Grand Prix circuit to test performance of the intelligent navigation system. During the test, a range of five to eight satellites were visible, except at the northwesternmost end of the test circuit where fewer than five satellites were visible. The circuit takes approximately 650 seconds to travel. The navigation system computed one position solution per second, or about 650 individual position solutions over the course of the circuit.

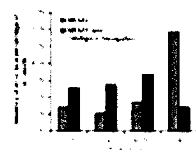


Figure 10 Magnitude and frequency of navigation error using the MEMS sensor during one circuit of the track

The test environment determined the performance of intelligent navigation with interference from external factors, such as satellite signal obstruction. This provided proof of concept that an integrated navigation system with intelligent navigation in an urban environment could provide an accurate, continuous navigation system.

One Circuit. To calculate the effectiveness of intelligent navigation, we navigated the test circuit both without and with the intelligent navigation system algorithms in operation. Figure 9 shows the road centerline as determined by the post-processed GPS measurements, and the derived positions from the MEMS inertial sensor. This plot clearly demonstrates the accumulation of error over time experienced by the MEMS sensors, with errors of as much as 200 meters present after 600 seconds.

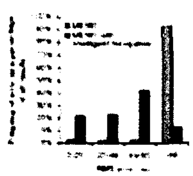
Intelligent Navigation, Inertial Integration

Double Assistance for GPS

May 1, 2002
By: Paul Cross, Allison Kealy, Stephen Scott-Young, Frank Leahy
GPS World

E-mail This Page

back Pages | 1 | 2 | 3



We then compared the navigation results epoch by epoch to the "true" position of the vehicle as measured by differential GPS. Table 2 shows the average distance (root mean squared or RMS) between the position of the vehicle calculated by the navigation system and the "true" vehicle position. Figure 10 shows the RMS errors that occurred during navigation.

Tables 3 & 4, Figure 11

Intelligent navigation significantly reduced the amount of error in the vehicle positions, with the majority of errors (86 percent) being less than 60 meters. Without intelligent navigation, the majority of errors (58 percent) were greater than 60 meters. These results demonstrate that the intelligent navigation algorithms reduce the RMS error to approximately one-third that of the navigation solution without intelligent navigation.

One Hour. Over a longer period of navigation, the accumulation of error in the MEMS measurement dramatically increases. Table 3 and Figure 11 demonstrate the accumulation of errors over one hour (32 kilometers) of navigation with the MEMS sensor around the test circuit.

After a sustained period of dead reckoning navigation, intelligent navigation enabled 87 percent of vehicle positions to have an error of less than 60 meters, while without intelligent navigation, 93 percent of positions had an error of greater than 60 meters.

Intelligent navigation can reduce the average RMS error from 573 meters and standard deviation of 378 meters to an average RMS error of 40 meters and a standard deviation of 18 meters. In fact, the MEMS-derived final point of navigation was over 1.2 kilometers different from the vehicle's actual location. Intelligent navigation reduced this accumulating error to 40 meters.

Signal Outage. In a realistic city driving scenario, urban canyons can cause navigation systems to function without GPS measurements for several minutes or more at a time. Simulating such an effect, Table 4 shows the navigation system's effectiveness using GPS measurements while sufficient GPS satellite signals can be received, and switching to the MEMS sensors when 220 seconds of GPS signal outage occurs. The average RMS error is shown both with and without intelligent navigation in use.

During the 220 seconds of GPS signal outage, the average accumulated error was 50 meters, however, intelligent navigation reduced this error to 10 meters. Over the total circuit, the uncorrected navigation system displayed an average error in each 1-second measurement of 12 meters, compared to an average error of 4 meters for the intelligent navigation system. The standard deviation of the navigation solution during the period of simulated GPS outage was also a factor of approximately five times better with intelligent navigation than without.

Conclusion

For many LBS, the availability of position without a sense of location renders the system virtually useless. As such, almost all LBS work off a digital map database to provide users with a sense of location by using visual clues within their environment. Errors of the order of magnitude offered by the GPS SPS can still place a user on an incorrect street. This situation is worsened in environments where GPS does not work and the DR system is left as the primary navigation system. The accumulation of errors over time can easily place the user well outside his or her actual location, making subsequent navigation almost impossible until the user can reorient.

Integrating spatial information with measurements from low-cost navigation sensors can improve the continuity and accuracy of the navigation solution in urban environments. The most significant impact of intelligent navigation is on DR navigation. Intelligent navigation largely eliminates the accumulation of errors, enabling sustained DR navigation without requiring input from absolute positioning devices.

By significantly reducing the accuracy requirements of navigation instruments, intelligent navigation enables the implementation of lower-cost instrumentation without compromising navigation performance. This combination of improved continuity and location accuracy establishes GPS and MEMS inertial sensors as essential components of the next generation of low-cost positioning sensors for stand-alone navigation.

Manufacturers

Performance of a low-cost MEMS inertial unit was simulated by extracting only partial results from a Crossbow AHRS-DMU attitude and reference heading system. A single Leica GPS500 receiver provided input to the intelligent navigation system, while two receivers recorded dual frequency carrier-phase observations to determine actual vehicle position. The project used GE Network Solutions Smallworld Core Spatial Technology GIS software.