Enhanced Positioning Performance using GIS-Assisted Satellite Positioning

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Abstract: This paper presents the initial results of research suggesting a concept of taking an advantage of known GIS information, primarily the ground elevation contour, to enhance the performance of satellite positioning systems in terms of improved availability and positioning accuracy. Recent advances of laser telemetry allow nowadays very accurate measurements of the Earth’s elevation down to sub-meter accuracy. Having such accurate information allows the Earth contour to be incorporated into the pseudorange solution equations by providing an additional relation between the horizontal position of the receiver and its height. This allows the removal of one unknown from the calculations of and hence requires one less satellite fix in order to provide a unique solution of the receiver position. This is especially important in shaded areas and urban canyons where it is difficult to ensure the visibility of at least four satellites (three in case of having already resolved the clock inaccuracy). The papers further various functions that may be used to approximate the ground elevation contours. Impact on expected position accuracy is also discussed. The research has been sponsored by the European Commission through the Integrated Project LIAISON under the Framework 6 programme (contract number: FP6-2003-IST-2-511766) [1].

I. Introduction

The Global Positioning System (GPS) [2] is a satellite-based system, operated by the U.S. Department of Defense, NAVSTAR (Navigation Satellite Timing and Ranging), which can be used to locate positions anywhere on the earth. It provides continuous, real-time, 3-dimensional positioning, navigation and timing worldwide. Any person with a GPS receiver can access the system, and it can be used for any application that requires location coordinates. The satellite signals require a direct line to GPS receivers and cannot penetrate water, soil, walls or other obstacles. For example, heavy forest canopy causes interference, making it difficult, if not impossible, to compute positions. In canyons (and "urban canyons" in cities) GPS signals are blocked by mountain ranges or buildings. A GPS receiver calculates its position by a technique called satellite ranging, which involves measuring the distance between the GPS receiver and the GPS satellites it is tracking. The range is measured as elapsed transit time. The first step in measuring the distance between the GPS receiver and a satellite requires measuring the time it takes for the signal to travel from the satellite to the receiver. Once the receiver knows how much time has elapsed, it multiplies the travel time of the signal times the speed of light to compute the distance. Since the clock on the receiver is not well synchronized with the atomic clock on the satellite, distance measurements to four satellites are required to compute a 3-dimensional (latitude, longitude and altitude) position and the estimate of the clock drift. The calculated position needs to be then related to the position on Earth.

The Earth geoid, unlike the ellipsoid, is irregular and commonly considered as too complicated to serve as the computational surface on which to solve geometrical problems like point positioning. The geometrical separation between it and the reference ellipsoid varies globally ±110 m. A reference ellipsoid used by WGS-84 is described by its semi-major axis (equatorial radius), a, and flattening, f. The locations of points in three-dimensional space are most conveniently described by three Cartesian or rectangular coordinates, X, Y and Z. Since the advent of satellite positioning, such coordinate systems are typically geocentric: the Z axis is aligned with the Earth’s (conventional or instantaneous) rotation axis. It is only because GPS satellites orbit about the geocentre that this point becomes naturally the origin of a coordinate system defined by satellite geodetic means, as the satellite positions in space are themselves computed in such a system. The GPS system uses geocentric coordination called ECEF ("Earth Centered, Earth Fixed"), where the axes are attached to the solid body of the Earth and the X axis lies within the Greenwich observatory’s meridian plane.

The recent advances in laser telemetry allow currently to survey ground elevation stripped from man made infrastructure at very high-resolution. One of the relatively new technologies is LIDAR (Light Distance And Ranging) [3], also known as Airborne Laser Swath Mapping or ALSM, which employs an airborne scanning laser rangefinder to produce accurate topographic surveys [4], down to 15cm resolution. The method relies on measuring the distance from an airplane, to the Earth’s surface by precisely timing the round-trip travel time of a
brief pulse of laser light. The travel-time is measured from the time the laser pulse is fired to the time laser light is reflected back from the surface. The reflected laser light is received using a small telescope that focuses any collected laser light onto a detector. The travel-time is converted to distance from the plane to the surface based on the speed of light. Surveys from LIDAR are well suited to aid in enhancing satellite positioning.

II. Pseudorange Solution Equations

Theoretically only four pseudoranges are required to calculate the position of the receiver. In practice receivers use as many satellites as are visible. In addition to this other information such as carrier phase, difference measurements for eliminating bias, Doppler frequency and sensor inputs can also be used. In this paper, however, we limit the discussion to the use of GIS ground elevation contour for pseudorange calculation for the case of two and three satellites in view only, which when using standard approach does not allow accurate position calculation of the receiver. Considering that the Earth elevation is known, the z-coordinate can be calculated from the plane to the surface based on the speed of light. Surveys from LIDAR are used, however using extra elevation information would allow the increase of positioning accuracy.

The solution can then be calculated iteratively until the resulting Δx=H'TΔρ is arbitrarily small enough. For the case of four or more satellites visible (over-determined problem) standard approaches should be used, however using extra elevation information would allow the increase of positioning accuracy.

III. Ground Elevation Contour

The ground elevation information is usually provided by GIS providers, such as Navteq, in terms of topographic contours. Such data requires a lot of storage as each topographic layer is coded the sequence of lines using latitude and longitude coordinates. For example the Navteq elevation database of Europe with 5m layer-to-layer spacing occupies 160MB in shape format. Considering that it identifies elevation above the mean sea level, this requires conversion into standard WGS-84 coordinate system. Furthermore in order to interpret such information in an iterative position calculation procedure requires approximating a 3D surface function through the set of elevation layers in the area of interest. A classic approach would be to use non-linear functions allowing to model accurately large areas of complicated shapes of elevation. The 2D trigonometric approximation function such as 2D cosine series can be used:

\[ F(x,y) = \frac{1}{M \cdot N} \sum_{k=0}^{N} \sum_{m=0}^{M} a_{k,m} \cos \left( 2\pi \left( k x / N + m y / M \right) \right) \]
The function (5) resembles the 2D representation of the frequency spectrum of equally spaced (sampled) digitised data. Using such a series of cosine functions, commonly used in the DSP, allows the coefficients to be calculated through standard 2D DFT. In order to apply the DFT, the elevation the data needs first to be discretised in both X and Y coordinates to the uniform grid, e.g. at a spacing of 5-10m, corresponding to the required positioning accuracy. The parameters of the approximation series can be then determined by:

1. Performing 2D DFT on the elevation data
2. Low-pass filtering to smooth the approximation
3. Using the most significant cosine components

Considering that coding and decoding large data sets using high order cosine functions would be computationally very expensive, the approximation functions should be defined for each of the variable-size geographical areas (Figure 2). The size of the area can be selected such that for the given order of the approximating function \((N, M)\) the error of approximation is within the required limits. In order to simplify the definition of the coverage areas we propose using rectangular grid with variable sizes.

\[
f_1(x,y) = \sum_{i=0}^{N} \sum_{j=0}^{M} \alpha_{i,j} \cdot x_i^i \cdot y_j^j
\]  

(7)

Polynomial regression leads to very accurate results as shown in Figure 3. On the other hand obtaining the polynomial that fits to the data from a large geographical area to a level of single meters requires still very high function orders.

In case of having at disposal dense elevation grid (at meter accuracies) it is possible to employ simpler forms of the 3D polynomial function approximation, such as the surface fit. In such a case \(N=M=1\) and \(a_{11}=0\), which simplifies (7) to:

\[
z_u(x_u, y_u) = \alpha \cdot x_u + \beta \cdot y_u + \gamma
\]  

(8)

The shape of the ground elevation can then be modelled using a mesh of non-crossing triangular surfaces as shown in Figure 4. Such an approach allows simplifying the solution of receiver position by linearization since function derivatives over \(x_u\) and \(y_u\) are constants.

IV. Geometrical Effects

A GPS device calculates the position using a technique called “3-D multilateration,” which is the process of figuring out where several spheres intersect. In the case of GPS, each sphere has a satellite at its centre. The radius of the sphere is the calculated distance from the satellite, orbiting at a 20.200km from the Earth, to the GPS receiver. Ideally, these spheres would intersect at exactly one point, causing there to be only one possible solution.
to the current location, but in reality, the intersection forms more of an oddly-shaped area. In the ideal situation GDOP reaches the value of one, which is the highest possible confidence level to be used for applications demanding the highest possible precision at all times. Under certain situations and for large number of situations GDOP may reach even values less than one.

The lowest GDOP is achieved when the volume of the space defined by the satellites and the receiver is maximised. It can be proven that the condition is that satellites are equally spaced and the ranges between closest satellites cross at 90deg angles. For such a case it is possible to calculate the optimum “angle of visibility” being the angle of the cone enclosing all visible satellites:

\[ \angle V_{\text{max}} = 2 \cdot \cos^{-1} \left( \frac{1}{\sqrt{3}} \right) \approx 1.91 \text{rad} \approx 109.47^\circ \quad (9) \]

The value of (1) is independent from the number of satellites (minimum of three). Precision is said to be “diluted” when the area grows larger, which leads to dilution of precision.

Placing the Earth into the geometric configuration with GPS satellites improves the GDOP, which can be proven graphically as in Figure 5. The left picture shows an example of bad satellite geometry in which case Earth curvature would allow improving GDOP several times. Even in the case of good geometry (when range curves of different satellites cross at angles close to 90deg) the improvement is still noticeable. It is also possible to notice from Figure 5 that adding Earth elevation into the receiver position calculation does not change the optimum angle of visibility of GPS satellites.

VI. Simulation results

The initial tests have been performed simulating short-time losses of satellites during tracking mode of the receiver, similar to the real life urban canyon situations. Using simple surface fit approximation and the 5m resolution Navteq elevation data for Europe demonstrated the promising positioning performance of less than 10m for two satellites visible at one time. Since algorithms were designed in Matlab, pre-recorded GPS signals (sampled at the first IF) have been used. Tests using higher-order approximation functions, both polynomial and non-linear ones, are still ongoing.

VI. Conclusions and Future Work

This paper presents the results of initial research on the use of high resolution ground elevation information for aiding in provision of position in situations when less than four satellites are visible (typical for urban canyon and other difficult signal propagation situations). The suitable 3D fitting functions were discussed and the use of surface fit was analysed. The latter one demonstrated its capability to provide acceptable results for most applications not requiring accuracies at more that half the distance between topographic layers and due to its simplicity to be suitable to portable platforms with limited computational capabilities.

The future work will concentrate on the extension of position calculation algorithms to incorporate high-order linear (polynomial) and non-linear (cosine expansion) functions. The use of dedicated location server (extending the capabilities of the LIAISON system) for providing correction data will be investigated. Use of tracking data collected from the number of served users for enhancing the accuracy of the ground elevation data will also be addressed.

REFERENCES

[1] LIAISON WEB site: http://liaison.newapplication.it/

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