VEHICLE LOCALIZATION IN URBAN CANYONS USING GEO-REFERENCED DATA AND FEW GNSS SATELLITES

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Abstract: Global Navigation Satellites Systems (GNSS) alone can provide very accurate positioning - few centimeters in real-time if the satellites visibility is very good and if there is no multi-track or refraction of the RF signals. Unfortunately, when a vehicle evolves in urban areas these conditions are rarely satisfied: the computed location can be much debased and even not possible, if less than four satellites are directly visible or if the geometry is badly configured with a poor GDOP. A way to tackle such a problem can consist in using the pseudo-ranges measured by the GNSS receiver (instead of using its navigation solution) and in fusing them with other data sources like for instance proprioceptive sensors. In this paper, we study the use of a priori charted data managed by a Geographical Information System (GIS). We focus here on the use of a road network provided by cartographers like NavTeQ or TeleAtlas. We explain how to use such information in the computation fix: the geo-referenced data is modeled as a linear segment that can be used as a constraint or fused with the pseudo-ranges. The underlying problem of choosing the good segment (known as the road selection problem) is also treated in this paper. We proposed a new method that uses the residuals to do this selection. Experimental results performed in Compiegne illustrate the interesting performance of this approach since the map-matched location can be computed using only 3 satellites and a usual 2D map in urban canyons.

Keywords: Outdoor Localization, Global Navigation Satellites Systems, GIS data, tightly coupled data fusion

1. INTRODUCTION

The positioning of an intelligent vehicle with respect to a given map is an important issue for many robotics applications. For instance, the map information is very useful for trajectory planning (Jabbour *et al.*, 2006) or for contextual information retrieval. In some applications, this information can be natural landmarks stored as Geographical Information and used for a precise positioning (Remazeilles *et al.*, 2004). Global Navigation Satellites Systems (GNSS) like GPS, Glonass or Galileo are very promising and affordable tech-

nologies for robotics. We can imagine that each vehicle will be soon equipped with a GNSS receiver. The problem that consists in localizing a vehicle with respect to a map is known as map-matching. Usually this problem is tackled using GNSS fixes, i.e. position solutions computed using pseudo-ranges and ephemeris data. This approach has the main drawback to need at least four satellites in line of sight.This condition is rarely satisfied in urban canyon (Georgiev and Allen, 2004). An alternative consists in using a tightly coupled approach in which the map information is used in

the computation of the fix. This is the approach considered in this paper. We focus here on the use of a road map provided by cartographers. The available information describes the centerline of the carriageways in a 2D representation. The main difficulty consists in using such information in the GNSS computation. We propose in the following an approach to reach this goal. We show how to construct a navigation frame in which the position of the satellites at their emission time is known. By supposing first that the road is known, we show how to compute a location. Then, we propose a strategy to select the most likely road by using the residuals of the computation. Experimental results carried out with our experimental show the performance of the approach: the method is able to work in an urban canyon using only 3 satellites. The paper is organized as follows. Section 2 will remind how a stand-alone GPS fix is computed, then several methods for map-aided GPS positioning will be presented in Section 3. In Section 4 a simple road selection algorithm will be presented. To conclude, Section 5 will show some experimental results obtained using the presented road selection algorithm and the map-aided GPS positioning.

2. STAND-ALONE GPS POSITIONING

GNSS positioning is based on the multilateration principle: measuring the time of flight between a receiver and four SVs (Space Vehicles), it is possible to compute the 3D position of the receiver in a ECEF (Earth Centered, Earth Fixed) frame using the WGS84 geodetic system. In this section, we present a method to compute an approximate position of the satellites before carrying out the localization computation, under the hypothesis that the receiver clock is approximately synchronized with the GPS time. This method is not necessary for GNSS stand alone computation. It will be useful for the fusion with the Geographical Information System (GIS) data.

2.1 SV estimated positions

SVs broadcast in real-time ephemerids data that contains Keplerian parameters describing their orbits. Given a GPS time-stamp t_e^i, it is possible to compute an estimate position of the SV at this time index in the $\text{ECEF}(t_e^i)$, since ECEF rotates with the earth. The receiver has to solve the following problems:

(1) What is the emission time t_e^i of the sequence sent by SV i ?
(2) What was the position SV i at time t_e^i in $\text{ECEF}(t_e^i)$?
(3) What is this position in the current ECEF?

The receiver estimates the time of flight t_{flight}^i of a sequence broadcast a SV, by measuring the shift between the emitted frame and its locally generated replica (C/A code):

$$t_{flight}^i = t_r - t_e^i \qquad (1)$$

Where t_r is the reception time and t_e^i is the emission time in the GPS time reference system. t_{flight}^i is in the order of 70ms. Unfortunately, there is an internal clock bias in the receiver compared to the GPS reference time. At the reception time, the receiver reads its clock $t_u(t_r)$. We have:

$$t_r = t_u(t_r) + dt_u \qquad (2)$$

The emission time is therefore given by:

$$t_e^i = t_u(t_r) + dt_u - t_{flight}^i \qquad (3)$$

If the internal clock bias of the receiver is kept small, then t_e^i can be approximated by

$$\hat{t}_e^i = t_u(t_r) - t_{flight,measured}^i \qquad (4)$$

Using $\hat{t}_e^i$, it is possible to compute an estimated position $X_{sat}^i = \left(x^i(\hat{t}_e^i), y^i(\hat{t}_e^i), z^i(\hat{t}_e^i) \right)$ of SV i in the frame $\text{ECEF}(\hat{t}_e^i)$ using the broadcast ephemeris. See (Kaplan, 2000) for details.

Now, we need to express the SV position X_{sat}^i in $\text{ECEF}(t_r)$. If we model the earth rotation by a simple 24 hours periodic rotation around z axis (ECEF coordinates), then the earth rotation angle between emission and reception times is:

$$\alpha_{earth}^i = \omega_{earth} \cdot t_{flight,measured}^i \qquad (5)$$

Using the angle express in 6, a single yaw rotation between $\text{ECEF}(t_e^i)$ and $\text{ECEF}(t_r)$ is done.

2.2 Receiver position computation

To compute the position of the receiver, let consider now the pseudo-range measurement ρ^i done by the receiver on SV i:

$$\rho^i = c \cdot t_{flight,measured}^i \qquad (6)$$

where $t_{flight,measured}^i$ is the measured time of flight. Like the receiver, SV i has an clock offset:

$$t_e^i = t_s(t_r) + dt_s^i \qquad (7)$$

So, we can rewrite the pseudo-range measurement as:

$$\rho^i = c \cdot (t_r - t_e^i) + c \cdot (dt_u - dt_s^i) \qquad (8)$$

Where c is the speed of light in vacuum. Let denote R^i the geometrical distance between SV i and the receiver in ECEF(t_r) frame:

$$R^i = \sqrt{(x+x^i(t_e^i))^2 + (y+y^i(t_e))^2 + (z+z^i(t_e))^2} \quad (9)$$

$$R^i = c \cdot (t_r - t_e^i) \quad (10)$$

For simplification, let us assume that dt_s^i can be precisely known using the ephemerids data. The corrected pseudo-range ρ_c^i is given using Eq.8:

$$\rho_c^i = R^i + c \cdot dt_u \quad (11)$$

Using Eq.9 and Eq.11, a relationship between corrected pseudo-range measurement for a SV and the receiver position and its internal clock bias has been built. Assuming n visible SVs, we can write a state vector X an observation vector Y:

$$X = [x, y, z, dt_u]^t \ , \ Y = [\rho_c^1, \cdots, \rho_c^n]^t \quad (12)$$

A non-linear equation system is obtained. If $n > 4$, then the system is also redundant. It is a static positioning problem that can be solved using an iterative least squares method or a Bancroft non-iterative method. Those methods are not explained here. We invite readers to refer to (Kaplan, 2000) and (Yang and Chen, 2001).

3. USING A ROAD SEGMENT IN THE POSITIONING COMPUTATION

We now intend to introduce the geographical information in the position computation. To illustrate this concept, let us use a digital road map. Under the hypothesis that the current evolution segment is known, we present in this section two ways to use the cartographic data.

3.1 Road maps

A road map is a database that contains a vectorial description of the road network. Roads are described in a discrete way by their center-line. The data associated with a road is classified in three groups:

- Geographical information: a segment set describing the geometry road
- Topological information: description of connectivity between roads segments
- Semantic information: Road name, speed limit, etc...

Actually, numerical road maps can achieve a metrical precision, which is sufficient to many navigation tasks, like route planning.

3.2 Working Frame

In order to compute a valid tightly coupled GNSS/map-matching positioning solution, a common working frame is necessary. Let recall that GPS provides ephemerids data in the WGS84 Cartesian frame whereas maps depict earth surface using planar projection such as Lambert93 in France (conformal conic projection).

Using the geographical data of the map, let us determine a tridimensional local frame such as (O, i, j) is tangential to the WGS84 Earth reference ellipsoid, since the elevation is not available in an usual map.

Suppose the system has in memory a "cache" of the roads around the current position of the vehicle. The origin O is chosen to be the origin of the first node. The x axis is defined as the first following shape point of the first road. The plane (O, i, j) is defined by a shape point of another road (in the working frame, all the map points have $z = 0$).

An homogeneous transform is therefore computed to obtain a WGS84 Cartesian position in the local frame:

$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}_{loc} = T_{WGS84 \rightarrow loc} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}_{WGS84} \quad (13)$$

3.3 Plane Constraint for Computation

Let suppose that the good road segment has been selected from the road points given by the GIS. The constraint defined by this selected segment is a piece of a vertical plane (in the working frame), since the elevation of the map is unknown. In practice, we consider the whole plane and we check afterwards that result matches with the segment.

Taking $A(a_1, a_2)$ and $B(b_1, b_2)$ as the extremity of the segment, the segment defines a straight line:

$$y = b_1 + \frac{b_2 - a_2}{b_1 - a_1} \cdot (x - a_1) \quad (14)$$

The geometrical equation of the constraint means that only the computation along (x, y) is constrained:

$$\begin{cases} y = f_1(x) \\ z = var \end{cases} \quad (15)$$

3.4 First method: Unknown Elimination

This method has been proposed by Cui and Ge in (Cui and Ge, 2003). The idea is to eliminate
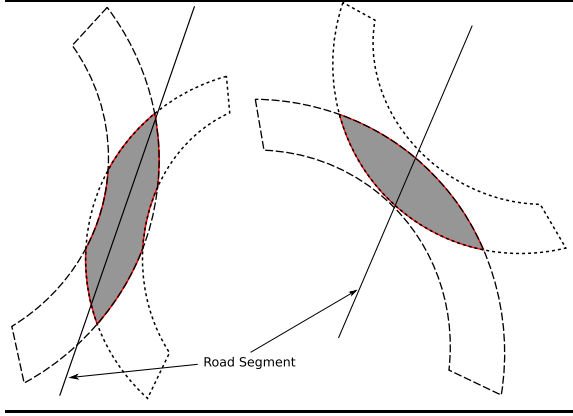
Fig. 1. Incertainity aera according to SV position regarding the road direction: on the left, 2 satellites are seen transversally; on the right, they are seen in the direction of the road.

a variable using the constraint equation. Introducing Eq.15 in Eq.9, the geometrical distance between the receiver and SV i can be rewritten as:

$$R^i = \sqrt{(x+x^i(t_e))^2 + (f_1(x)+y^i(t_e))^2 + (z+z^i(t_e))^2} \quad (16)$$

This new expression of the geometrical distance gives a new non-linear system:

$$\rho_c^i = h^i(x, z, dt_u) \ , \ \forall i = 1, \cdots, n \qquad (17)$$

The problem dimension is now reduced and the minimal number of needed SVs to achieve the computation of positioning solution is now 3. Since the constraint is strong, the computed position belongs to the constraint plane. Please note that its projection onto the map can be outside of the segment.

3.5 Second method: Plane Fusion

This method has been proposed by S. Syed and M.E. Cannon in (Syed and Cannon, 2004). Using the segment parameters, a new observable is built. Therefore, it is possible to add a new equation to the observation model defined using Eq.14:

$$\begin{array}{c}(b_1-a_1){\cdot}a_2+(a_2-b_2){\cdot}a_1=(b_1-a_1){\cdot}y+(a_2-b_2){\cdot}x \\ \rho_c^{n+1} = h^{n+1}(x, y, z, dt_u)\end{array} \quad (18)$$

With this additional measurement and at least three SVs, the positioning solution can be computed. Contrary to the unknown elimination method, the computed solution doesn't belong to the constraint plane defined by the road segment.

3.6 SVs position relative to road heading

The geometrical configuration of the SV versus the current segment is crucial. Let consider 2 SVs

the positions of which are projected onto the two-dimensional map frame thanks to their azimuth and elevation angles. Theirs measurements can be compared to circles of radii $\rho \pm \epsilon$ where ϵ defines the uncertainty of the measurement. Assuming the vehicle is moving on a charted road, the longitudinal precision provided by the GNSS is more important to achieve a good positioning. According to Fig.1, one can intuitively notice that if the SVs are located in the direction of the road, they provide a better positioning information than those orthogonal to the road.

4. ROAD SELECTION ALGORITHM

We have seen how a road segment information can be introduced into the positioning solution computation. A road selection algorithm is proposed in order to select the evolution segment that best matches the current GNSS observations. In order to reduce the road selection algorithm processing time, a road cache has been extracted from the map around a first GNSS fix.

4.1 Candidate segments extraction

For each segment in the road cache, a tightly coupled positioning solution is computed using the unknown elimination method described previously in Section 3.4 in order to determine the corresponding matched point. Therefore, a non-linear equation system like Eq.17 is solved for each segment. A fix solution is computed using the Newton-Raphson Least Squares iterative solver. A segment can be considered as a candidate if:

- The projection of the fix onto the reference plane $(0, i, j)$ belongs to the considered segment.
- The fix elevation is close to 0 in the local frame (i.e. lower than an user's defined threshold).

Please note that this stage can provide no segment. This can indicate large map errors or bad GNSS observations.

4.2 Positioning solution residuals

As the positioning solution is computed using a Newton-Raphson iterative solver with a fixed number of iterations, we suggest to use the residuals. Indeed, they allow defining a consistency value in order to choose the most probable segment:
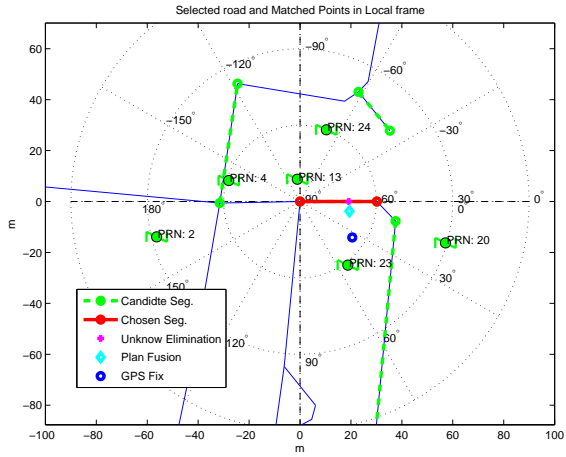
$$Res = |Y - H \cdot dX| \qquad (19)$$

where:

Fig. 2. Road selection results and positioning solution using all visible SVs

- Y is the measurement
- H is the Jacobian matrix of the observation equation
- dX is the residuals vector of the computation.

4.3 Most likely segment selection

Without any a priori information on the vehicle position, the segment with the better consistency is chosen as the most likely segment. Otherwise, if the vehicle position on a segment is known with good accuracy at one moment, then a connex candidate segment is preferred.

5. FIRST EXPERIMENTAL RESULTS

5.1 Methodology

Experiments have been carried out in two stages. The first stage dealt with data recording and the second with data exploitation. Data has been recorded using our laboratory experimental vehicle *strada* and a GPS receiver type *Trimble 5700* in a stand-alone mode. The data recording has been done on a road next to the lab and this road has been well identified in the geographical database. SVs measurements were recorded using *Rinex 2.10* observation file format and the corresponding navigation file has been used.

We analyze in this section the road selection algorithm and the tightly coupled GNSS-Map fusion using a single fix. For simplicity, the local frame has been set along the current evolution segment. Therefore, the (O, i) axle coincides with the good segment. Please notice that this segment in reality is not East oriented. Moreover, the SVs used in the position computation have been superposed on the map using a *skyplot* graphic which allows to estimate their elevation and azimuth angles respectively with the origin of the local frame.
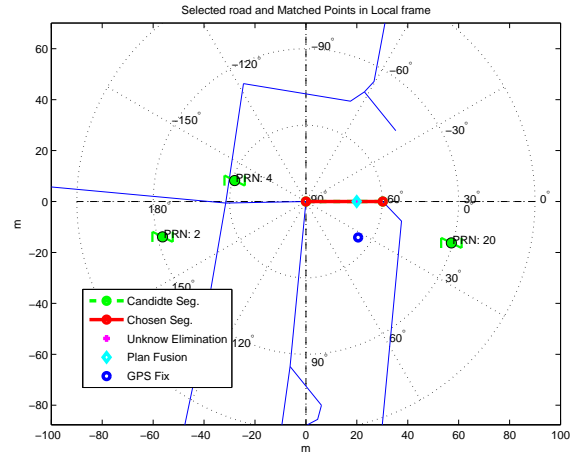

Fig. 3. Road selection and position using three SVs near to the road axle

5.2 Results using 6 SVs

As shown by Fig.2, let consider what happens if all the 6 visible SVs are used for the computation.

4 segments are claimed to be candidate (those plotted in dash) and the current evolution segment has been correctly chosen as the most likely segment (plotted in bold). As presented in Section 3, the positioning solution computed using the unknown elimination method has correctly eliminated the incorrect segments, because they have provided solutions outside of the segments or too far from the horizontal frame of the map. Moreover, if we examine the result of the autonomous GNSS fix, we can observe a significant bias in the map data (about 12 meters). This result show that the presented algorithm is efficient for a simple road selection since there is little ambiguity due to the other candidate segments. The relevance of the proposed tightly coupled GNSS-Map matching using the constraint plane is therefore shown.

5.3 Impact of SVs configuration in the position computation

Let us now appreciate experimentally the impact of SVs configuration with respect to the road in the positioning solution computation. As shown on Fig.3, only the SVs with azimuth near to road heading are used where as, on Fig.4, the SVs used are orthogonal to road direction.

We can see that, when the SVs are spread along the segment axle, the correct evolution segment is the only one claimed to be a candidate (and obviously selected). When using the SVs that are not along the segment axle, the correct evolution segment doesn't belong to the candidate segments list and the result of the computation is incorrect. Further more, we can notice that all the candidate segments direction are near to the axis made by
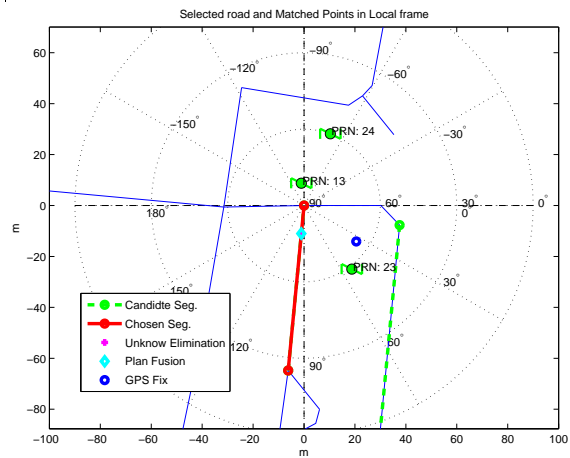
Fig. 4. Road selection and position using three SVs orthogonal to the road axle

the SVs and, in this case, orthogonal to the evolution segment. This result proves experimentally the analysis done on Fig.1: in a urban canyon the visible satellites are naturally well configured for a tightly coupled GNSS-Map computation and only 3 are sufficient.

We have also remarked that, when using few SVs, the positioning solution computed with both methods introduced in section 3 are equivalent. This comes from the fact, that when using few SVs, the weight of the constraint plane in the observation model grows up and so attracts the matched point next to the road segment.

6. CONCLUSION AND FUTURE WORK

In this paper, we have described two methods to fuse road map data with GNSS rough measurements (L1 pseudo-ranges). This approach has several advantages. First, as shown by the experiments, it is possible to use only three satellites to compute a fix. Secondly, since the selection of a segment is necessary, the map-matching problem is can be solved using the residuals of this computation. The main difficulty arises from the need to compute a GNSS fix using the pseudo-ranges and particularly to locate the satellites thanks to the ephemerid data in a frame attached to the map. We have proposed a method that supposes that the clock drift of the receiver is small. Therefore, the position of the satellites at their emission times can be easily determined in the frame of the map. In order to solve the segment selection problem, we have proposed a simple search strategy. The results that we have obtained are very encouraging since the method is able to retrieve the good segment. We have also confirmed experimentally that the satellites that are the most interesting for the solution computation are those that are in the axle of the road, which is the situation occurring in urban canyons. The perspective of

this research is on the use of a dynamic state observer (for instance a Kalman filter) to take benefice of the road connectedness, particularly while approaching junction. Moreover, we plan also to use WAAS/EGNOS corrections to increase the reliability of the method.

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