A STUDY OF CITY BUILDING MODEL BASED POSITIONING METHOD USING MULTI-GNSS IN DEEP URBAN CANYON

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ABSTRACT

The current global navigation satellite systems (GNSS) receiver cannot calculate satisfactory positioning results in urban environment due to multipath and non-line-of-sight (NLOS) effects. The research team of The University of Tokyo developed a particle filter based positioning method using a basic 3-dimension city building to rectify the positioning result of commercial GPS single frequency receiver. This developed method is achieved by implementing particle filter to distribute possible position candidates. The likelihood of each candidate is evaluated based on the similarity between the pseudorange measurement and simulated pseudorange of the candidate. The expectation of all the candidates is the rectified positioning of the proposed map method. The evaluation of using QZSS L1-submeter-class augmentation with integrity function (L1-SAIF) correction to the developed pedestrian positioning method is also previously discussed. However, the visible satellite in deep urban canyon using only GPS and QZSS would be not very enough for the developed method. The use of the immerging multi-GNSS, such as GLONASS, Galileo and Beidou, could be a potential solution to the situation of lacking of satellites for the developed method. The real data are recorded in two of the most famous urban canyon, Shinjuku and Hitotsubashi, at Tokyo, Japan using a commercial grade u-blox GNSS receiver. According to the experiment result, the availability of positioning solution will increase with the aid GLONASS and QZSS.

Introduction

GPS provides accurate and reliable positioning/timing service for pedestrian application in open field environments. Unfortunately, its positioning performance in urban areas still has a lot of potential to improve due to signal blockages and reflections caused by tall buildings. The signal reflections can be divided into multipath and non-line-of-sight (NLOS) effects. Recently, to use 3D building model as aiding information to mitigate or exclude the multipath and NLOS effects has become a popular topic of study. In the beginning, the 3D map model is used to simulate the multipath effect to assess the single reflection environment of a city [1]. The metric of NLOS signal exclusion using an elevation-enhanced map, extracted from a 3D map, is developed and tested using real vehicular data [2]. An extended idea of identifying NLOS signals using infrared camera set at an automotive vehicle was suggested [3]. The potential of using a dynamic 3D map to design a multipath exclusion filter for a vehicle-based tightly-coupled GPS/INS integration system was studied in Obst et al. [4]. A forecast satellite visibility based on a 3D urban model to exclude NLOS signals in urban areas was developed in Peyraud et al. [5]. The above approaches aim to exclude the NLOS signal, however, the exclusion is very likely to cause a HDOP distortion scenario, due to the blockage of buildings along the two sides of streets. In other words, the lateral (cross direction) positioning error would be much larger than that of the along track direction. As a result, approaches that apply multipath and NLOS signals as measurements become essential. One of the most common methods, the shadow matching method, uses 3D building models to predict the satellite visibility and to
compare it with measured satellite visibility to improve the cross street positioning accuracy [6]. A multipath and NLOS delay estimation based on software defined radio (SDR) and 3D surface model based on particle filter was proposed and tested in a static experiment in the Shinjuku area [7]. The research team of The University of Tokyo developed a particle filter based positioning method using a 3D map to rectify the positioning result of commercial GPS single-frequency receiver for pedestrian applications [8]. The evaluation of the QZSS L1-submeter-class augmentation with integrity function (L1-SAIF) correction to the proposed pedestrian positioning method is also discussed in Hsu et al. [9]. However, the visible satellite in urban canyon using only GPS and QZSS would not be enough for the proposed method. The use of the emerging multi-GNSS, such as GLONASS, Galileo and Beidou, could be a potential solution to the situation of lack of visible satellites for the proposed method. The objective of this paper is to assess the performance of the proposed pedestrian positioning method using GPS, GLONASS and QZSS.

3D Building Models Construction and Ray-Tracing Technique

This paper establishes a 3D building model by a 2D map that contained building location and height information of buildings from 3D point clouds data. The Fundamental Geospatial Data (FGD) of Japan, which provided by Japan geospatial information authority, is open to Japan public. This FGD data is employed as 2D geographic information system (GIS) data. Thus, the layouts and positions of every building on the map could be obtained from the 2D GIS data. In this paper, the 3D digital surface model (DSM) data is provided by Aero Asahi Corporation. Fig. 1 shows the process of constructing the 3D building model used in this paper. This paper firstly extracts the coordinates of every corner of buildings from FGD as shown in the left of Fig. 1. Afterwards, the 2D map is integrated with the height data from DSM with it. The right of Fig. 1 illustrates an example of a 3D building model that established in this paper. The developed 3D building map contains very small amount of data for each building in comparison to that of the 3D graphic application. This paper only contains the frame data of each building instead of the detail polygons data of building. This basic 3D building map is utilized in the simulation of ray-tracing.

Fig. 1. The construction of the 3D building map from a 2D map and DSM.

The ray tracing used in this paper is according to from the ray-tracing technique addressed in [10]. This paper does not consider diffractions or multiple reflections because these signals occurred under unfavorable conditions. Thus, this paper only utilizes the direct path and a single reflected path. The developed ray-tracing simulation can be used to
distinguish reflected rays and to estimate the reflection delay distance. This paper assumes that the surfaces of buildings are reflective smooth planes, namely mirrors. Therefore, the rays in the simulation obey the laws of reflection. In real world, the roughness and the absorption of the reflective surface might cause the mismatch between the ray-tracing simulation and the real propagation. This paper neglects this effect due to the roughness of the building surface is much smaller compared to the propagation distance. The detail of the ray-tracing algorithm used can be found at [8].

3D Map-Based Pedestrian Positioning Method

The flowchart of the developed 3D city building model based particle filter is shown in Fig. 2.

As shown in Fig. 1, this method firstly implements a particle filter to distribute position candidates (particles) around the previous estimated and receiver estimated positions. In the Step 2, when a candidate position is given, the proposed method can evaluate whether each satellite is in LOS, multipath or NLOS, by applying the ray-tracing procedure with a 3D building model. According to the signal strength, namely carrier to noise ratio (C/N₀), the satellite could be roughly classified into LOS, NLOS and multipath scenarios [8]. If the type of signal is consistent between C/N₀ and ray-tracing classification, the simulate pseudorange of the satellite for the candidate will be calculated. In the LOS case, simulated pseudoranges can be estimated as the distance of the direct path between the satellite and the assumed position. In the multipath and NLOS cases, simulated pseudoranges can be estimated as the distance of the reflected path between the satellite and the candidate position via the building surface. Ideally, if the position of a candidate is located at the true position, the difference between the simulated and measured pseudoranges should be zero. In other words, the simulated and measured pseudoranges should be identical. Therefore, the likelihood of each valid candidate is evaluated based on
the pseudorange difference between the pseudorange measurement and simulated pseudorange of the candidate, which simulated by 3D building models and ray-tracing. Finally, the expectation of all the candidates is the rectified positioning of the proposed map method. The proposed method is therefore able to find the optimum position through a dedicated optimization algorithm of the above assumptions and evaluations. The detail algorithm of the particle filter using 3D city building models can be found in [8, 9]. The positioning principle of the proposed method is very different from the conventional GPS positioning method, i.e., WLS. As a result, the calculation of the positioning accuracy of the 3D map method should be also different. We define two positioning performance measures for the 3D map method: URA3Dmap and positioning accuracy. The value of user range accuracy of the 3D map method (URA3Dmap) is to indicate its level of positioning service, which is similar to the user range accuracy (URA) of conventional GPS [11]. The URA3Dmap is defined based on the percentage of the valid candidates from all candidates outside the building. The higher percentage of the valid candidate implies a higher confidence of the estimated position. Ideally, if the center of the candidate distribution is not far from the ground truth, the simulated pseudorange of the candidates located at the center of distribution would be very similar to the measurement pseudorange, as shown in the left of Fig. 6. Fig. 6 shows two typical cases of high and low confidence of positioning results. In this case, the confidence of the proposed 3D map result is much lower than the other cases. Accordingly, this paper defines the URA3Dmap as listed in Table 1.

<table>
<thead>
<tr>
<th>URA index</th>
<th>range accuracy</th>
<th>URA3Dmap index</th>
<th>Percent of the valid candidate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4 m – 3.4 m</td>
<td>1</td>
<td>75%~100%</td>
</tr>
<tr>
<td>2</td>
<td>3.4 m – 4.85 m</td>
<td>2</td>
<td>50%~75%</td>
</tr>
<tr>
<td>3</td>
<td>4.85 m – 6.85 m</td>
<td>3</td>
<td>25%~50%</td>
</tr>
<tr>
<td>4</td>
<td>6.85 m – 9.65 m</td>
<td>4</td>
<td>10%~25%</td>
</tr>
<tr>
<td>5</td>
<td>9.65 m – 13.65 m</td>
<td>5</td>
<td>5%~10%</td>
</tr>
<tr>
<td>6</td>
<td>13.65 m – 24.0 m</td>
<td>6</td>
<td>&lt;5%</td>
</tr>
</tbody>
</table>

Table 1. The definition of URA [11] and URA3Dmap used in this paper.

Experiments and Discussion

This paper selects the Hitotsubashi and Shinjuku areas in Tokyo to construct a 3D building model because of the density of the tall buildings. In this area, multipath and NLOS effect are frequently observed. This paper tests pedestrian navigation in a typical path that includes walking both sides of street and passing through/waiting at a road intersection. The cut-off angle is 20 degree. The data were collected on 5th November 2014 and 17th December 2014. Two single point positioning methods compared in this paper, one is single point positioning solutions provided by open source RTKLIB software (RTKLIB SPP) [12] and the other is the proposed 3D map method. RAIM FDE of the RTKLIB SPP is used in this paper as a conventional NLOS detection algorithm. This paper uses a geodetic-grade GNSS receiver, the NovAtel FlexPak 6 GNSS receiver, and a commercial grade receiver, the u-blox EVK-M8 GNSS model. The NovAtel receiver is only used to collect the QZSS L1-SAIF correction signal. The u-blox receiver is set to output pseudorange measurements and positioning results every second. In this paper, a quasi-ground truth is generated using a topographical method. The video cameras are set in the 18th floor and 9th floor of a building near the Hitotsubashi and Shinjuku area, respectively, to record the travelled path. The video data output by the cameras are used in combination with one high-resolution aerial photo we bought to get the ground truth data. The aerial photo is 25cm/pixel and...
therefore the error distance for each estimate can be calculated. The synchronization between video camera and commercial GNSS receiver is difficult to be perfect in the topographical method. As a result, this paper uses point to “points” positioning error to evaluate the performance of dynamic experiment. The synchronization error is limited to 1 second in this paper. Hence, for each estimated position \( x(t) \), the ground truth points used to calculate the positioning error is \( x_{\text{GT}}(t-1), x_{\text{GT}}(t) \) and \( x_{\text{GT}}(t+1) \). The point to “points” positioning error is calculated as below.

\[
\varepsilon_{p2ps}(t) = \min_{t-1 \leq s \leq t+1} |x(t) - x_{\text{GT}}(s)|, \quad (1)
\]

There are three performance metric used in this paper, mean, standard deviation of the point to points error and the availability of positioning solution. The availability defined in the paper means the percentage of giving solution in a fix period. For example, if a method outputs the 80 epochs in 100 seconds, the availability of the method is 80%. There are two dynamic data demonstrated in this paper. The skyplot of the data are shown in Fig. 3. The satellites shown in Fig. 3 are tracked by the u-blox commercial receiver. The two dynamic data are typical signal receptions at Hitotsubashi (middle) and Shinjuku (deep) area.

In order to study the benefit of using different GNSS constellation in the 3D map method, Fig. 4 shows the trajectory estimated by the proposed method under different satellite constellation. The different color in Fig. 4 indicates different value of URA\(^{3\text{Dmap}}\) of each point. This trajectory is divided into five sections for the purpose of better discussion as shown in the right of Fig. 4. To observe the GPS only case (left of Fig. 4), the result of A and B sections has much better performance than that of section D and E. The reason is because more than half of the GPS satellites will be block at the D and E sections as shown in the left of Fig. 3. The trajectory after using GLONASS is shown in the middle of Fig. 4. It is obvious that the positioning results located at the right side of street is greatly increased. This improvement is sourced from the increasing number of satellite in view. However, the quality of GLONASS signal is not as good as GPS because of the multipath effect has double effect on GLONASS. In summary, the positioning error of applying GLONASS maintains at similar level, and availability increases about 12% compared to using GPS only. The right of Fig. 4 is the result after adding QZSS L1 C/A and L1-SAIF. Comparing the left and middle of Fig. 4, the results of the C, D and E sections are increased. This is because the QZSS provides a high elevation angle satellite to the 3D map method. As a result, the valid candidates of the points at C, D and E section are increased dramatically. The reliability in
C, D and E sections are much higher than that of GPS+GLONASS. In addition, the trajectory became smoother than before. The comparison of the positioning result of both RTKLIB SPP and the proposed 3D map method using GPS only, GPS+GLONASS, and GPS+QZSS+GLONASS are listed in Table 2. As addressed in Table 2, the positioning performance of the 3D map method using GPS, GLONASS, and QZSS has the best performance among three scenarios. The positioning error mean and availability are 3.89 meters and 96.72%, respectively. It is interesting to note the positioning error mean could be further improved to 3.23 meters if selecting the position point with URA_{3Dmap} \leq 3 (yellow, orange and red points in Fig. 4). This selection will lose about 17% of availability.

A similar experiment is conducted in the Shinjuku area of Tokyo city and the positioning results are shown in Fig. 5 and its skyplot is shown in the right of Fig. 3. The comparison of the positioning result of both RTKLIB SPP and the proposed 3D map method using GPS only, GPS+GLONASS, and GPS+QZSS+GLONASS are listed in Table 3. As can be seen in the left of Fig. 5, the half of the solutions of GPS-only are on the correct side of the street. Only a few points are incorrect due the insufficient number of satellite. With the adding of GLONASS measurements, the availability of the proposed method is greatly increased. Besides, most of the outliers in the GPS-only solutions are corrected. As a result, the positioning error mean is improved from 6.51 to 4.76 meters and the availability is improved from 62.31% to 76.81%. The GLONASS measurements could provide a great aid because the satellite distribution of GPS and

### Table 2

The performance comparison of RTKLIB SPP and the proposed 3D map method using different combination of satellite constellation in middle urban canyon.

<table>
<thead>
<tr>
<th></th>
<th>RTKLIB SPP</th>
<th>3D map method</th>
<th>3D map method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (m)</td>
<td>Std (m)</td>
<td>Avail.</td>
</tr>
<tr>
<td>GPS-only</td>
<td>17.24</td>
<td>20.41</td>
<td>76.23%</td>
</tr>
<tr>
<td>GPS+GLONASS</td>
<td>18.04</td>
<td>19.27</td>
<td>79.92%</td>
</tr>
<tr>
<td>GPS+GLONASS+QZSS</td>
<td>19.41</td>
<td>22.71</td>
<td>87.30%</td>
</tr>
</tbody>
</table>
GLONASS are complementary. After adding the QZSS measurements, the availability is increased by 92.75% again. However, the positioning error mean is increased to 6.29 meters. It is interesting to note the positioning error mean could be further improved to 5.27 meters if selecting the position point with URA_{3Dmap} ≤ 3. Although this selection will lose about 20% of availability, however, it could be easily compensated by a simple filtering technique. To compare Table 2 and Table 3, we can find the positioning error of the proposed method in the middle urban canyon is about 1 to 2 meters worse than that in the deep urban canyon. The reason for this degrade is because of the increase of multiple reflected NLOS.

![Fig. 5. The positioning results of the proposed 3D map method using different combination of constellation in middle urban canyon.](image)

<table>
<thead>
<tr>
<th>RTKLIB SPP</th>
<th>3D map method</th>
<th>3D map method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (m)</td>
<td>Std (m)</td>
</tr>
<tr>
<td>GPS-only</td>
<td>26.84</td>
<td>27.82</td>
</tr>
<tr>
<td>GPS+GLONASS</td>
<td>22.53</td>
<td>35.25</td>
</tr>
<tr>
<td>GPS+GLONASS+QZSS</td>
<td>18.11</td>
<td>27.93</td>
</tr>
</tbody>
</table>

**Conclusions**

In this paper, we proposed 3D city building model based positioning method using multi GNSS in deep urban canyon. NLOS is main cause of the error that has been removed by the proposed ray tracing method. In the experiment and discussion sections, we evaluated the result using mean, standard deviation of the point to “points” error and the availability of positioning solution in the Hitotsubashi and Shinjuku of Tokyo. The positioning error maintains at similar level and availability is increased in all case, when GLONASS and QZSS is utilized. In particular, we can obtain more
precise positioning result if selecting the position point with URA3Dmap $\leq 3$.

Acknowledgements

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Reference


