Corrective Track Form Matching for Real-Time Pedestrian Navigation

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Abstract—The Global Navigation Satellite Systems (GNSS) receivers often have difficulties within the urban setting. And indoors the ordinary receivers do not function. For a short term periods, but extended to the long, like Zampella et al. [5], city updates are important areas that need to be corrected sensor navigation system.

The corrective track form matcher consists of two parts. A short track form matcher compares the PDR track against the GNSS track and infers anomalies in the GNSS track. The short track form matcher tags the GNSS measurements as reliable or unreliable. The long track form matcher uses the reliable GNSS measurements and transforms the PDR track by weighting these good quality measurements more. The accuracy (error limit of 96%) in the test case improves from 7.56 m to 4.39, this is by 1.72 times.

Keywords—track form matching; pedestrian dead reckoning; GNSS; fusion; navigation; track-to-track

I. INTRODUCTION

Indoor navigation draws an increasing attention. As the technologies develop, the emerging new services for the public will follow. One of the remaining challenges is the development of an accurate navigation system for pedestrians. The current service level for the public can barely offer proximity information in the shopping centers and similar environments.

In an urban setting, the GNSS receiver is not capable to follow the user accurately. Especially the multipath and gaps in the positioning measurements are common with the current technologies used in the mobile devices.

This paper presents a novel corrective track form matching method to fuse the foot-mounted inertial measurement unit data with the GNSS positioning data. The section II examines the background. The section III introduces the research challenge. The section IV explains the idea of the short track form matching. The section V depicts the idea of the long track form matching. The section VI analyses the test conducted. The section VII concludes the work.

II. BACKGROUND

The foot-mounted inertial pedestrian dead reckoning (PDR) provides relative position change information. It characteristically has an error of few metres after walking a few tens of meters. This error is dependent on the standoff quality and the user’s walking style. If the user stops often and shuffles their feet a lot, the harder it is for the dead reckoning system to follow the user. Ju et al. [1] studied the heel-strike and toe-off performance for the foot-mounted pedestrian dead reckoning. The gait phase and the implementation details of the zero velocity updates are important areas that need to be developed to be more accurate. Altun and Barshan [2] further mention that the error produced by the loose mounting of multiple inertial units at chest and the feet should be taken into account.

The GNSS receiver functions well in an open area with a good line of sight conditions to the satellites. When surrounded by trees or buildings the multipath and attenuated GNSS signals make the receiver position information unreliable. In addition, the position error information is unreliable. The work of Hsu et al. [3] describes trials made with dead reckoning on mobile phone and the GNSS measurements in the middle of urban canyons.

To compensate for these troubles, previous research work has been conducted. The use of heterogeneous, complementary sensors is a necessity for dealing with varying situations arising in urban and indoor scenarios. Pelka et al. [4] aim to create an architecture that is generally applicable for multi-sensor positioning in different situations.

The most obvious application of track form matching is within the map matching methods, like Zampella et al. [5] describe. The user trail is matched with the existing map information. Xu et al. [6] used a grid based map to aid the WiFi and magnetic heading sensor navigation system. Aggarwal et al. [7] used a heuristic map matching to compensate for the heading drift. Points on the map are matched with the points from the dead reckoning trajectory. The drift can be eliminated, depending on the map and the road layout. Our application, in this paper is similar strategy of matching, but extended to the matching between the inertial dead reckoning trail and the GNSS trail. In this paper we do not use matching with the map.
Lan and Shih [8] mention three geometrical similarity testing methods. The shape filter is based on selecting a centroid for the trail under inspection and then dividing the trail into sections by using straight lines that all go through this centroid point. The crossing points between the trail under inspection and the straight lines are compared. The similarity is then derived by these crossing point comparison between the two trails under inspection using a threshold value. The angle filter and the edge filter collect the angle of the trail and the edges at different points. This angle and edge information of the trail is again compared with that of the map node information. The appearance similarity, the pairwise geometric attributes and the structural likelihood are derived in [9] using line detection with map nodes and the GNSS data. In our work, we use the angle and correlation information of the PDR and GNSS trails using three points. Further, seven points are used for the track shape geometrical similarity comparison.

Liu and Shi [10] use the right angled corridors in the map to correct the magnetic heading information. Jimenez et al. [11] matched a light database with the PDR trail. Using a waist mounted magnetic orientation sensor outdoors together with a PDR system, a more complex drift estimation is presented by Song and Park [12], where a cascaded Kalman filter estimates both the walk course angle and the foot heading angle. Lee et al. [13] developed straight walk detection and trail corner detection methods and used these with map matching. In our work we have both the foot heading and the course angle information. This is important to be distinguished since the GNSS trail angle can be compared directly with the course angle but not with the foot heading angle.

In [14], Lera et al. analysed leisure movement patterns, in hiking, against the map node information. This was to reveal whether the weather and seasons affect the use level of different hiking trails and the services along them. Xu et al. [15] developed a track fusion reliability algorithm. First they removed the outliers in the different sensor subsystems. Then they associated the tracks with reliability information before fusing the most reliable trails. Tian and Bar-Shalom [16] review the track to track fusion methods. These can include no memory, partial memory or full memory of the trails to be fused. Our approach has partial memory since we use the latest section of the PDR and the GNSS tracks in the comparison and fusion process. In this paper, we concentrate on the real-time processing of a one user trail and on a corrective measurement update that is processed after approximately 30m when we have gathered enough track information for the comparison adjustments.

III. PROBLEM AND TEST CASE DEFINITION

The GNSS trail is often affected by the multipath in the urban setting. The buildings and trees block the direct line of sight to the satellites. This makes the GNSS trail often to deviate as is described in [3].

The inertial pedestrian dead reckoning remains accurate for few tens of meters. Although, this depends on the situation where the user is and how they are behaving. In this work the user is walking normally and at constant speed the whole time. Further research could include the special cases of shuffling and other sudden and hardly trackable behaviour, in terms of the motion mechanism. We trust the PDR system is able to provide a trail of continuous walking within 5 % error after 30 metres walk. The previously developed adaptive fusion engine of an inertial foot-mounted PDR system and the positioning fixing systems and trials using this system can be found in [17, 18]. It is based on the 15 error state Kalman filter.

Using this foot-mounted PDR system and a GNSS receiver (Microstrain 3DM-GX4-45 with laptop running Debian), we define the problem. A walk with very high quality GNSS measurements was conducted, where the GNSS trail quality is close to the reference system quality. The reference system was the Leica RTK. We then add six disturbances to the GNSS track of which the longest is approximately 50m. These added anomalies resemble the test runs that had multipath-like disturbances present. The Fig. 1 shows the GNSS trail (magenta), the added disturbances (yellow) and the result of the foot-mounted PDR system when only Zero Velocity Updates are used (cyan). The heading and starting position are correct in the beginning. The start and end point are shown on the map.

There are six added disturbances. The characteristics of these disturbances are a duration of below 50 meters and deviations of up to 15 meters. Moreover, for the measurements with the used GNSS receiver (u-Blox 6, 4Hz sampling), the deviation is not often sudden but rather a subtle shift.

IV. SHORT TRACK FORM MATCHING

The PDR system is very reliable for a few tens of meters if the walking motion is constant, regular and with no shuffling, stops and no other sudden movements. This is the condition for
the test walk we conducted. A context determination module between shuffle and normal walking should be added for the future research of the method.

The short track form matching consists of three points on both the GNSS track and the PDR track. The first point is at the current estimated position on both of the tracks. The second and the third point follow behind by predefined intervals. We implemented three short track form matchers. The interval for the first was 5 meters, for the second 10 meters and for the third 15 meters. Thus, we trust the PDR track up to 30 meters.

The three points make up two lines, in between which there is an angle. This angle is compared between the GNSS and the PDR track by applying a threshold value. This is the first method for the GNSS disturbance detection. The GNSS is defined as disturbed if the threshold is exceeded.

The second detection method is similar, but examines the relative form of the three points using the corr2 function in MATLAB. The three points on both of the tracks are overlayed first, so that the oldest points (point 3) match and the distance between the current track point and the middle point are minimal by turning the PDR track around the oldest point. A threshold value separates the GNSS disturbance detection from a non-disturbed GNSS trail. Fig. 2 shows the detection process.

The results of the short track form matchers are available after 30 meters. This means that the short track form matching information can be used after walking this distance.

The short track form matching is performed at defined intervals. At every second, during the test walk, the GNSS track is tagged with the result of the comparison process. Either good or bad quality tag is placed for the whole three-point track under test.

V. LONG TRACK FORM MATCHING

The long track form matching examines seven points on both the GNSS and the PDR track. These seven points need to be of a good quality on the GNSS track. Thus, if the GNSS quality was tagged bad by the short track form matcher the next point is selected that has a good quality GNSS tag.

The two first points of the short track form matchers are not selected for the long track form matching since they might still change. The first point for the long track form matching is then the last point of the short track form matching (point 3). The six of the points are then the points in the history with a condition that they are of a good quality. Thus the length that the seven points constitute between each matching depends on the results of the short track form matching. The Fig. 3 depicts the selected seven points.

Fig. 2. The short track form matchers consist of three points at different intervals (5, 10 and 15 meters). The angle or the correlation between the three points are examined via a threshold value.

Selection of the seven points for the long track form matching.
In the middle, the short track form matcher has tagged the GNSS track as of a bad quality. These points are not used in the long track form matching.

Fig. 3. The long track form matcher consist of seven points at three seconds intervals.

The time is set as the definer for the interval length and it works when the user is in constant motion. Length could be considered as an alternative option. The interval between the points is three seconds. This means that if the GNSS track is all the time being tagged good the seven points on the track cover the distance traveled during 21 seconds. If there are bad quality tags the track form matching method waits until new good quality points are encountered.

A. Matching the seven points

A centroid for the seven points is defined for both tracks. The PDR track section is then moved so that its centroid matches with that of the GNSS track. After this, the PDR track is rotated 360 degrees to find the minimum error for the least squares distance between the seven corresponding points.

Thirdly, the PDR track is moved so that the oldest points match with the two tracks. Fig. 4 depicts the process.

PDR track is moved so that the centroids match. Then the angle with the smallest error of least squares distance between the corresponding seven points is searched. Then the PDR track is moved so that the oldest positions match.

Fig. 4. The PDR track is moved so that the centroids match. After, the angle is searched with which the error distance between all corresponding points is minimal. Finally, the PDR track is moved so that the oldest points match.
B. Applying a correction

After the angle for the centroid is found and the PDR track is moved so that the oldest points match, a correction is applied.

The correction is a highly weighted position update. The error is measured between the first points of the PDR and the GNSS track. This error is then suppressed in the error state Kalman filter by applying a position error update that moves the current PDR track position according to this error vector.

Also a moderate attitude update, similarly than in [19], is applied, if the first two points are tagged as of a good quality, according to the difference angles between the PDR and GNSS trails and if they are near (within 10 m) to each other. The difference between the PDR and GNSS attitudes is used to turn the PDR towards the GNSS direction if the condition for the two first points apply. This is weighted moderately since the GNSS track could consist of turns that would make the update inconsistent. The Fig. 5 depicts the correction phase.

The seven-point track section is smoothed after the position and possible attitude updates. The shift that the position update created is applied to the whole of the track with a lowering percentage. The shift is applied 100% for the current point and with lowering percentage for the rest of the track section so that for the point 7, the last point, the shift is applied by 0%.

Likewise, as the PDR track was moved there is thus a jump between the oldest point (point 7) and the older track before the seven-point track section. This is smoothed similarly up to the point 8, which is the previous good quality GNSS track point before the point 7. The Fig. 6 shows this smoothing process.

The seven-point track form matching starts after the seven points have been defined. This is after the short track form matcher has defined seven points.

We now have the real-time track, with lightly weighed GNSS measurements, and also the corrected and smoothed track applicable after a new good quality GNSS point is tagged.

The correction consists of applying a position update. The position error between the points in the PDR and GNSS tracks is applied to the current position.

Also a moderate attitude error update is applied if the first two points of the GNSS track are tagged as good quality.

The thresholds are manually placed. As a future work, an artificial learning database of multipath situations could be fed to a process that would define the most fit threshold settings before applying into the new test sets.

A. Short track form matcher detection analysis

The three short track form matchers were used for the original PDR and the GNSS track with the added disturbances shown in Fig. 1. Fig. 7 shows the detection results. The table 1 shows the detection matching results with different angle and correlation thresholds.

The best accuracy when applying the long track form method was found for the angle detection method (19,5 degrees) at the maximum detection success percentage (76,07%). For the correlation detection method this wasn’t the case. A tighter limit for the correlation had to be used to achieve an accuracy close to the angle method accuracy. For the correlation method the best accuracy wasn’t achieved with the best detection percentage, but with tighter correlation limit of 0,9918.
The angle method was approximately 7% more successful. The final accuracy of the method is presented in the next section, where the long track form matching affects the detection success. The long track form matching changes the PDR trail and thus affects the detection success.

<table>
<thead>
<tr>
<th>Threshold value</th>
<th>Detection success %</th>
<th>Detection method</th>
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</thead>
<tbody>
<tr>
<td>17,5 degrees</td>
<td>72,47 %</td>
<td>Angle</td>
</tr>
<tr>
<td>18,5 degrees</td>
<td>72,92 %</td>
<td>Angle</td>
</tr>
<tr>
<td>19,5 degrees</td>
<td>76,07 %</td>
<td>Angle</td>
</tr>
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<td>20,5 degrees</td>
<td>75,39 %</td>
<td>Angle</td>
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<td>21,5 degrees</td>
<td>75,17 %</td>
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<td>0.9816</td>
<td>68,99 %</td>
<td>Corr2</td>
</tr>
<tr>
<td>0.9918</td>
<td>68,88 %</td>
<td>Corr2</td>
</tr>
</tbody>
</table>

B. Long track form matcher accuracy

Fig. 1 shows the PDR track before the GNSS updates and before the track form matching updates have been applied. The Fig. 8 depicts the fusion with the moderately weighted GNSS measurements (cyan) and with the combined lightly weighted GNSS measurements and the heavily weighted long track form matching updates (white).

It is clearly seen that the track form fusion track matches the true track much better than the simple moderate fusion of the GNSS measurements. The light weighting of the GNSS measurements retains the correct form of the track. This light weighted track is then “bent” so that it follows the good quality GNSS measurements more. The short track form detection dropped from 76,07 % to 74,94 % for the 19,5 degrees’ case.

![Fig. 1](image1.png)

![Fig. 8](image2.png)

Fig. 7. The detection method comparison. The yellow means that an anomaly is detected. The magenta describes a track where GNSS and PDR tracks match. The angle detection method (above) detection success of anomalies differs from that of the corr2 method (below).

The cyan track is the PDR fusion with the moderate GNSS weighting. The white track is the PDR fusion with light GNSS weighting and heavy long track form matching weighting.
The PDR and GNSS fusion is the cornerstone of the GNSS trail (red) and the moderate GNSS accuracy after the short track form matching updates were used. The short track form matcher was used. The accuracy after the long track form correction reaches the accuracy of the moderate GNSS and PDR fusion accuracy before the long term track form matching updates are applied (blue). These are compared with the moderately fused GNSS and PDR tracks (black).

The error of the GNSS trail with the added anomalies is 9.12 metres (96% of error). This is in magenta in the Fig. 9. The original GNSS error (red) is 4.07 metres (96%). The real-time error in the Fig. 9 of the PDR and GNSS fusion is the accuracy before the long term track form matching updates are applied. This is shown in green and is 7.40 metres (96%). It is slightly better than the moderate PDR and GNSS fusion (black), which has an error of 7.56 metres (96%). After the long track form correction update the PDR and GNSS fusion (blue) reaches an accuracy of 4.39 metres (96%), which is close to the original good quality GNSS trail accuracy without the added anomalies.

VII. CONCLUSIONS

The constant moderately weighted GNSS position measurement fusion without the knowledge or reliability of the measurement quality resulted in an accuracy (96%) of 7.56 metres. Our method improves the fusion slightly in real-time (7.40 metres error). Whenever the short track form matcher provides information of the estimated good quality GNSS measurements, the long track form matcher corrects the fusion track by weighting these good quality GNSS measurements more using the long track form matching update method. The accuracy after the correction is 4.39 metres, which is 1.72 times better than with the moderate GNSS fusion.

The short track form matcher uses the angle and the correlation method for the detection of the GNSS anomalies. In this work we have trusted the PDR track up to 30 metres. Naturally, if the PDR is not reliable within this limit the method starts to fail. The reliability, or the error of the PDR track in this work was assumed to be below 5% for 30 metres walk.

The correlation method was found to be slightly less accurate in the detection. Only three points of the PDR and GNSS tracks were fed to the corr2 function in Matlab. The detection success and the fusion accuracy and behaviour study using more points in the corr2 function is the next research task.

Three different short track form matchers were used. The same threshold was used for each matcher. Further trials could be introduced by trying separate values for each of the matchers. Moreover, an artificial inference process could be used by feeding the learning process known training sets of multipath-affected GNSS trails. A wider variety of the multipath anomalies would then need to be included in the test set as well, to offer a more detailed study of the method.

The long track form matcher corrects the PDR track. For the introduced anomalies the correction works very well and an accuracy near to the original GNSS track without the anomalies is reached. Although, when we examine the Fig. 8, we can see that the track is off the reference by few metres at the north road (northing 40, easting -40). This was the longest introduced anomaly. It was approximately 50 metres. Our method corrects the shorter anomalies well. In the 50 metres anomaly we see the effect of the PDR track reliability. The PDR guides the track to the right. This was the tendency of the PDR as is seen in the Fig. 1 PDR trail. For longer anomalies within the GNSS trail, the novel method will have less corrective effect. This is expected, since we have not used additional corrective information for these longer anomalies. Map matching would help, especially in urban canyons, which are often longer than 50 metres. Using the long track form matcher with similar heavily weighted updates from a map matcher is the next obvious study for the method.

The long track form matching method uses a light GNSS weighting fusion for the real-time solution. A corrective heavily weighted GNSS fusion is applied whenever the short track form matcher tags the GNSS quality as good. More levels could be added into the GNSS quality inspection and fusion process. This is, the GNSS fusion could be fuzzified further. For example, if the GNSS receiver can provide somewhat reliable error information, this could be used for the GNSS fusion. That is, instead of the light real-time GNSS weighting that we used, we could use moderate weighting for the GNSS measurements if the receiver assumes the quality to be better, and light GNSS weighting when the receiver informs of low quality GNSS measurements.

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REFERENCES


