Collaborative Positioning - Concepts And Approaches for More Robust Positioning

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Key words: cooperative positioning, sensor fusion, Kalman filter

SUMMARY

Collaborative or cooperative positioning techniques (CP) have been adopted from the field of wireless sensor networks as an approach to improving the navigation and positioning performance for a range of human and land vehicle navigation applications. This is particularly relevant for those applications operating in GNSS challenged environments where requirements for positioning availability cannot be met and/or which are safety critical, requiring higher levels of reliability and integrity. CP techniques typically leverage an available communications infrastructure to share information between users operating within a defined neighbourhood or so-called ad hoc network. This shared information can be integrated to deliver more robust positioning performance. Under certain conditions, the communications infrastructure itself can be used as a measurement source for positioning. For example, Dedicated Short Range Communications (DSRC) infrastructure which is being deployed in many countries to facilitate a range of Intelligent Transportation systems (ITS), has the potential to provide a ranging measurement between vehicles in a vehicular ad hoc network (VANET). What is emerging as a significant consideration for CP are the benefits for positioning in terms of availability, integrity, reliability and accuracy versus cost in terms of infrastructure, computational overheads and the overall quantity and quality of information that needs to be shared to meet the positioning requirements of a specific application.

In this paper, the broad applicability of CP algorithms and techniques for land mobile applications is discussed. A range of qualitative and quantitative measurement information that can support CP is presented such as low cost MEMS based inertial sensors, map matching and DSRC. An initial cost benefit assessment of these 'measurements' is undertaken, in addition to considerations for determining the point of diminishing marginal utility for positioning i.e. at what point does the integration of additional information provide a negligible return to the positioning performance. This is an important step forward in redefining the concept of ubiquitous positioning from the traditional idea of integrating all available signals of opportunity, towards identifying the optimal set of measurements for the requirements of the application i.e. fitness for use. In this paper, measurements collected during field experiments conducted under a joint FIG working group (5.5) and IAG sub commission (4.2.1) entitled Ubiquitous Positioning and their use across a range of CP research efforts is summarised and presented.
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1. INTRODUCTION

Robust positioning is typically described in terms of performance metrics including accuracy, availability, continuity and accuracy. These metrics have been fully defined in the aviation community where safety critical needs have mandated requirements for standards of positioning performance. Similar trend are evidenced in the maritime sector with the international maritime organisation (IMO) developing standards for positioning based on current and future capabilities of Global Navigation Satellite Systems (GNSS). The land mobile sector however, has lagged significantly behind these performance based standards and there are currently no formal specifications for land based applications. The emerging capabilities of Cooperative Intelligent Transport Systems (C-ITS) have significantly changed the landscape for positioning information and in particular, positioning quality. C-ITS are driving the development of an increasing range of safety and liability critical applications that expect certain levels of positioning performance in order to realise the maximum benefits for improving road safety and efficiency of the road network.

In aviation(Ochieng et al, 2013), the metrics used to describe positioning quality are: accuracy is defined as the degree of conformance of an estimated or measured position at a given time to a defined reference value; integrity relates to the level of trust that can be placed in the information provided by the navigation system. It includes the ability of the navigation system to providetimely and valid warnings to users when the system must not be used for the intended operation or phase of flight. Specifically, a navigation system is required to deliver a warning (an alert) of any malfunction (as a result of a set alert limit being exceeded) to users within a given period of time (time-to-alert); continuity of a navigation system is its capability to perform its function without non-scheduled interruptions during the intended period of operation; availability is defined as the percentage of time during which the service is available (i.e. reliable information is presented) for use taking into account all the outages whatever their origins. The service is available if accuracy, integrity and continuity requirements are satisfied.

What is evident across these definitions is that their computation is based on the availability of sufficient measurements that not only facilitate computation of the position solution but typically will enable the identification and potential adaptation of incorrect or spurious measurements. To ensure that sufficient measurements are available, the majority of positioning solutions rely on the integration of multiple sensors and signals. These hybrid solutions typically integrate GNSS with measurements from inertial navigation sensors or similar in-vehicle sensor systems. The error characteristics of these inertial sensors are such that, over periods of prolonged GNSS outages as experienced in dense urban environments, the overall positioning outcome deteriorates significantly. Over recent years,
another emerging technique is being proposed to overcome the shortcomings of GNSS, often termed as Cooperative Positioning (CP). It is a technique which allows vehicles within a vehicular ad hoc network (VANET) to share positioning related information with other vehicles or infrastructures in trying to improve their positioning solutions.

In this paper, the broad applicability of CP algorithms and techniques for land mobile applications is discussed. A range of qualitative and quantitative measurement information that can support CP is presented such as low cost MEMS based inertial sensors, map matching and DSRC. An initial cost benefit assessment of these "measurements" is undertaken, in addition to considerations for determining the point of diminishing marginal utility for positioning i.e. at what point does the integration of additional information provide a negligible return to the positioning performance. This is an important step forward in redefining the concept of ubiquitous positioning from the traditional idea of integrating all available signals of opportunity, towards identifying the optimal set of measurements for the requirements of the application i.e. fitness for use. In this paper measurements collected during field experiments conducted under a joint FIG working group (5.5) and IAG sub commission (4.2.1) entitled Ubiquitous Positioning and their use across a range of CP research efforts is summarised and presented.

2. COOPERATIVE NAVIGATION CONCEPT

Cooperative positioning (CP) is a technique which can potentially overcome the shortcomings of GNSS for a range of ITS applications. CP originated in Wireless Sensor Networks research where individual nodes are able to share information with other nodes in its "neighbourhood" in order to localize the network of nodes as a whole. One advantage of CP is that the localization accuracy, integrity, availability and continuity is expected to improve with the node density (number of neighbour vehicles used in collective localization).

In the context of C-ITS, the nodes are vehicles within a road network neighbourhood called a Vehicular Ad-hoc Network (VANET), see Figure 1. The CP approach relies on information being shared between vehicles within a VANET, to overcome the limitations for positioning in difficult environments such as high-rise, dense urban areas, where multipath effects and the complete or partial obscuration of satellites limit GNSS positioning capabilities. The sharing of information between vehicles can only be achieved through the availability of a communications infrastructure that supports information exchanges between vehicles in the VANET and/or between vehicles and roadside infrastructure. Dedicated short-range communications (DSRC) is a wireless communication channel designed specifically to support vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. In the U.S., the Federal Communication Commission (FCC) has allocated DSRC with a dedicated bandwidth of 75 MHz in the 5.850-5.925 GHz band, whereas the European Telecommunications Standards Institute (ETSI) has allocated a dedicated bandwidth of 30 MHz in the 5.9 GHz band. Some of the planned applications of DSRC includes intelligent transportation system (ITS), traffic management, safety and efficiency as it is able to provide low latency, high speed communication, and strong and relative close proximity signals (Parker and Valaee, 2007), hence making it a suitable candidate for the enablement of CP techniques within a VANET. In fact, DSRC underpins plans in the US to develop telematics.
regulations that will require new cars and light trucks sold in the US to be equipped with systems for vehicle to vehicle communications. Raising concerns about privacy, the intention is for "vehicles equipped with DRSC chips to receive and process signals from nearby DRSC-enabled cars to learn their location, direction and speed. If a driver does not react to an impending collision, the car could then sound a warning or apply the brakes automatically to prevent an accident". Fundamentally, DSRC communications combined with a robust positioning capability and the core technologies are required to realise the significant benefits of C-ITS for road safety (TTAC, 2014).

In a VANET, the information shared between vehicles can be in the form of inter-vehicle ranges, relative speed, orientation, and satellite related data. This is the case when all or some of the nodes (vehicles) — so called anchor nodes — are equipped with GPS. The network collective positioning is done once the ranges and the position information are exchanged between the nodes. Sharing information could help the vehicles within the network to obtain positioning solutions even when the requirement of GNSS positioning cannot be met. The key considerations in developing a CP system are therefore (1) the sensor systems for positioning of individual nodes; (2) the communication subsystem; (3) an inter-node ranging sub system and (4) data fusion algorithms, see Figure 2.

In the next section, a summary of some of the approaches to address these considerations is presented along with an assessment of the improvements in positioning quality. The underlying motivation for this work is that the practical use of CP algorithms for C-ITS

Figure 1: CP positioning concept (from Intelligentdots, 2012).
applications requires a cost effective solution, both in terms of the in-vehicle positioning sub-system, the roadside infrastructure and the computational overhead. The focus is therefore on the use of low cost (such as MEMS based inertial navigation units) or “no cost signals of opportunity” (such as DSRC) to develop robust hybrid positioning solutions for individual vehicles. Our thesis is that through this approach, an optimal balance between infrastructure costs and performance can be achieved.

3. **LOW COST MICRO-ELECTROMECHANICAL SYSTEM (MEMS) INERTIAL NAVIGATION SENSORS (INS)**

Low cost MEMS inertial sensors (accelerometers and gyroscopes) are routinely considered for applications requiring positioning in difficult GNSS environments without a significant addition in terms of cost and form factor. It is therefore a likely candidate for use in the development of CP algorithms in which each node in the VANET computes its own hybrid solution based on GNSS and INS. What is emerging as significant in the use of low cost INS, is their applicability to the increasing range of safety and liability applications. Lane level positioning and collision avoidance require high performance positioning capabilities specifying higher levels of accuracy, integrity, continuity and availability than that required for vehicle route guidance. The increasing stability and improved performance of MEMS sensors combined with the potential for even further enhancements has driven the investigations of this research task - to evaluate the capabilities of MEMS technologies with the aim of delivering high performance positioning for C-ITS applications.

Field experiments to evaluate the quality of low cost MEMS sensors have been performed in an international cooperation of the joint International Associations of Geodesy (IAG) Working Group WG 4.1.1 and International Federation of Surveyor (FIG)WG 5.5 on “Ubiquitous Positioning Systems” with participating members of the University of Melbourne, Australia, the Ohio State University, Columbus, USA, the University of Nottingham, UK, the University of New South Wales, Sydney, Australia, the National Technical University of Athens, Greece, and the Vienna University of Technology, Austria at
the University of Nottingham in May 2012. These tests were conducted as part of a broader research agenda in CP, with multiple vehicles and personnel navigating simultaneously in different operating environments. Figure 3, shows the experimental setup for evaluating the performance of a range of commercially available MEMS sensors. A train was equipped with a Novatel GPS, a tactical grade Novatel SPAN IMU, and two MEMS-based IMUs, i.e., the Xsens MTi-G and the Systron Donner Inertial MMQG. The two MEMS sensors represent state-of-the-art in low cost MEMS sensors, and their performance was evaluated against that of the higher grade unit. Figures 4 and 5 show a comparison of accelerations and turning rates respectively between the MEMS MMQG sensor and the SPAN. Figure 6 shows the solutions obtained from the onboard GPS receiver (Single Point Position), the SPAN integrated solution and the computed MEMS INS/GPS integrated solution.

Although the MEMS sensors have higher noise levels than the SPAN IMU, the two data sets correlate well in terms of the rotations and accelerations made by the platform. It is often argued that the errors of inertial navigation, especially with commercial MEMS INS modules, rapidly increase over time due to integrations over the measured accelerations and angular velocities through the positioning process. This makes them difficult to integrate into a robust navigation solution as these errors tend to degrade significantly during significant periods of satellite outage, and regular updates from a GNSS are essential in order to contain the MEMS noise levels – which is not always possible in dense urban environments for example. There are many methods to combine INS and GNSS data to improve the performance of GNSS positioning. Some examples are presented in Carvalho et al, 1997; Hide et al, 2003 and Huang and Tan, 2006. These INS/GPS implementations cannot be classified as CP, as defined here, because the position-related data are not shared between separate nodes for data fusion.

A variety of analyses and compensation methods for inertial navigation errors are available in the literature. Some examples are presented in Lee et al, 2008; Fong et al, 2008; Akeila et al, 2008. Without entering into the details of these methods, we emphasize these techniques have a common attribute, the standalone approach. This means that error compensation solutions are conducted for a single user/node.

Figure 3: Train trajectory for MEMS INS testing

In the following section we show the benefits to GPS/INS of further improving the hybrid GPS/INS capability through the integration of range information between vehicles in the VANET. In addition, we contend that an assessment of the MEMS sensor from a qualitative perspective (see Figure 7) is informative from the perspective of identifying activity patterns in the data. This information offers other benefits for positioning – i.e. the ability to detect movement versus stopping can be useful in tuning the algorithms for sensor fusion.
Figure 4: MEMS INS performance tests - accelerations.

Figure 5: MEMS INS performance tests - turning rates.
4. INTER-NODE RANGING BASED ON DSRC

Radio based ranging determines the distance between vehicles in the VANET using time of arrival (TOA), time difference of arrival (TDOA) or Received Strength Signal (RSS) techniques. Parker and Vallee, 2008; Huang, et al, 2006 and Mao, et al, 2007, have shown that these techniques can be used in support of CP but that they also present major practical challenges for use in VANETs. For example, ranging using TDOA technique suffers severely in the presence of multipath. RSS on the other hand is difficult to model accurately as the signals are easily affected by reflection, scattering and diffraction which changes from one place to another. Non-radio based ranging techniques on the other hand, uses connectivity information (Mao, et al, 2007). Although less complex than radio based ranging techniques, most of these techniques are not suitable for VANETs due to their low positional accuracy (Doherty, et al, 2001 and Fayed, et al, 2007). However, the low level GNSS data sharing technique has produced some promising results as presented in Alam, et al, 2012. The study has shown that relative positioning using code based double difference between two moving vehicles can achieve better accuracy of relative positioning than differential GPS (DGPS).
However, the technique can only work when four common satellites are observed simultaneously.

Experiments were conducted as part of the Nottingham trials, in which two mobile mapping vans were equipped with a pair of DSRC transceivers. The important parameters for evaluating the functionality and performance of these equipment include the Received Signal Strength (RSS) observation noise, precision of the received packets time tags, Carrier Frequency Offset (CFO) observation noise, and the packet delivery rate. RSS is widely considered for radio ranging purposes in the literature for CP due to its simplicity. Here, the level of RSS observation noise of four DSRC equipment will be explained. CFO can also be used for ranging and position enhancement in vehicular networks. The accuracy of ranging depends on the CFO observation noise. Packet delivery rate depends on the number of competing nodes which use a common channel of DSRC for a specific application, for example CP. Only two transceivers were available for this experimental campaign and, therefore, the evaluation of packet delivery rate constraints was not possible technically. Here, we summarize the different parameters evaluated for the DSRC transceivers employed in this experimental campaign. For RSS and CFO observation noise, transmit power was set at two different levels, 10dBm and 20dBm. Table 1 shows the Standard Deviation (STD) of the observations for different conditions. As can be seen, the RSS observation noise is the same for both transmit powers, but the performance of CFO estimation improves when the transmit power is higher. This is consistent with the results for CFO estimation performance presented in Garello, et al, 2013 and Alam, et al, 2012 and similar articles.

For evaluating the precision of the received packets time tags, two different packet transmit rates were considered. For each case, the STD of the receive time tags with regard to the set rate was calculated. Table 2 shows the results. As can be seen, the time tags of the received packets have some uncertainty which is less for a higher transmit rate. Here, we do not have enough insight and motive to investigate this behaviour of timing in terms of transmission rate but considering the very accurate and high resolution of receive time tagging, in the order of ns, it can be concluded that such uncertainty is due to the transmit schedule at Physical Layer (PHY) of the DSRC transmitter. A more important issue is the order of the timing uncertainty. Although DSRC clocks were synchronised with GPS time, millisecond order is achieved which is absolutely useless for ranging purposes. Further investigations regarding the utility of DSRC for ranging between vehicles is currently underway.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transmit Power: 10dBm</th>
<th>Transmit Power: 20dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD of RSS observation noise</td>
<td>1.4dBm</td>
<td>1.4dBm</td>
</tr>
<tr>
<td>STD of CFO observation noise</td>
<td>135Hz</td>
<td>115Hz</td>
</tr>
</tbody>
</table>

Table 1: Standard deviation (STD) of the DSRC observations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transmit Rate: 10 packet/sec</th>
<th>Transmit Rate: 20 packet/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>STD of time tags around the anticipated receive times</td>
<td>2.3ms</td>
<td>1.6ms</td>
</tr>
</tbody>
</table>

Table 2: Standard deviation (STD) of two different packet transmit rates.
5. CP LOCALISATION ALGORITHMS

A localization algorithm is a computational algorithm that addresses the problem formulation, robustness, estimation accuracy, coordination and computational complexity, given some measurement information. The common theme in VANET localization is the employment of distributed localization algorithms (due to their ad hoc nature); however, a centralized, or hierarchical (i.e. combination of centralized and distributed) algorithm that advocates vehicle to infrastructure communication or even a hybrid/modal algorithm has its own appeal for higher accuracy and greater availability (i.e. reliability) (Costa, et al, 2006). According to Blum, et al, 2004, VANETs show frequent fragmentation, rapid topological evolution over time and short link life (e.g. less than a second for vehicles travelling in opposite directions). As such any localization algorithm must take these factors into account since communication overhead can overwhelm the network and exhaust its channel capacity. A CP algorithm for VANETs, must have the following characteristics: first it must be real time and very fast; second it must be adaptive with respect to the traffic conditions and/or the node density; third it must be robust to inter-node connection failure.

Monte Carlo Localization (Dellaert, et al, 2007), Convex Optimization (Doherty, et al, 2001), Iterative Multilateration (Tay, et al, 2006), and Multidimensional Scaling (MDS) (Blum, et al, 2004) are the most popular network localization techniques. Parker and Valaee, 2007 presented CP estimation for VANETs as a distributed positioning algorithm. They introduced an iterative algorithm based on LMSE. The algorithm had two steps: an initialization and a refinement. The initialization of an estimate of all vehicle positions was made through exchanging GPS information, trilateration by using three vehicles that were GPS-equipped (known as Adhoc trilateration). Each vehicle then uses all the other nodes’ information to make a more accurate position estimate: this was the refinement stage. In Parker and Valaee, 2007 they introduced an Extended KF to incorporate kinematic information of the vehicles into the position estimation. Two approaches investigated in this research addresses the use of the KF in (1) developing a hybrid CP algorithm that integrates map information and (2) a hybrid CP algorithm that integrates MEMS INS data. Many in-car navigation systems already provide map databases from which directional information is provided to the driver. These databases possess intelligent information that can be incorporated either as constraints to the KF solution or integrated directly as measurements within the filter. In this paper two map matching (MM) rules have been implemented. The first rule makes the assumption that the vehicle is travelling on a road (which is typically the case).This simple topological constraint can be included in the location solution, immediately improving the accuracy of the computed position of the vehicle. In the next sub-section we apply this rule to the KF solution. The simple algorithm is effective when the nearest road/lane to the estimated position (from GPS or other sources) 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 can downgrade the position solution. To overcome this problem, a second geometric MM rule applied in parallel takes into account the direction of the road the vehicle is travelling on. This second rule requires that the nearest road to which the vehicle’s position is corrected (using the first MM rule) must have a...
similar bearing to the direction of travel. This corrects the problems previously described. Figure 8 describes the algorithm architecture and Figure 9 presents the results based on simulated data which shows the positioning improvements achievable from using the MM information.

Figure 8: A CP module, consisting of positioning device (GPS unit), communication and ranging device (DSRC), computational processor (KF processing unit) and digital map.

Figure 9: Simulation result shows that KF with both MM rules have better performance than KF with second MM rule only and KF without MM.
In the second technique, vehicles communicate their ID, position estimate computed from dead reckoning, the Euler angles (determined from the INS measurements), and odometer-based speed estimates with the other vehicles travelling in the opposite direction. The technique has been termed Cooperative Inertial Navigation (CIN). The key idea for CIN is to determine the passage time and distance between vehicles travelling in opposite directions using the Doppler shift of the communication signal, in the case of a VANET the DSRC signal. At each vehicle, the INS navigation estimates are fused with those of the passing vehicle as well as the Carrier Frequency Offset (CFO) of the received packets from DSRC. Considering constraints on the geometry of the vehicles as they pass each other as well as their geometry with respect to the road network, better estimates of the dead reckoned vehicle position can be computed. Figure 10 shows the results obtained from tests conducted as part of the Nottingham trials. As can be seen, the proposed CIN method decreased the dead reckoning error at the time of passage of a vehicle travelling in the opposite direction and the consequent epochs as a result. This is due to the improved Euler angles and position estimates at the passage time using CIN.

![Figure 10: The performance of dead reckoning with and without CIN.](image)

6. CONCLUSIONS

Cooperative positioning (CP) techniques are a potential solution for meeting the accuracy, availability, integrity and continuity requirements of C-ITS. CP relies on the availability of a communications infrastructure through which vehicles can share information that can improve the overall positioning quality. In this paper, research activities under the IAG working group 4.2.1 and FIG working group 5.5 on ubiquitous positioning have been summarised. In particular, we have demonstrated the performance and role of low cost MEMS based sensors in CP algorithms. Results that demonstrate improved performance from hybrid positioning solutions with additional constraints from map matching and DSRC based inter node ranging have been presented. These preliminary results are encouraging and will motivate future algorithm developments that further improve the capabilities of GNSS/INS based CP.
7. ACKNOWLEDGMENT

The authors would like to acknowledge the contributions of members of the IAG WG 4.2.1 and FIG WG5.5. In particular the contributions of Nima Alam, Azmir Hasnur Rabain, Vassilis Gikas and Chris Danezis in collecting and processing of the data. Also, Professor Terry Moore and the technical staff at the University of Nottingham for hosting and supporting the data collection efforts.

8. REFERENCES


Collaborative Positioning – Concepts and Approaches for more Robust Positioning, (7053)
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FIG Congress 2014
Engaging the Challenges – Enhancing the Relevance
Kuala Lumpur, Malaysia 16 – 21 June 2014


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Guenther Retscher is an Associate Professor at the Department of Geodesy and Geoinformation of the Vienna University of Technology, Austria. He received his Venia Docendi in the field of Applied Geodesy from the same university in 2009 and his Ph.D. in 1995. His main research and teaching interests are in the fields of engineering geodesy, satellite positioning and navigation, indoor and pedestrian positioning as well as application of multi-sensor systems in geodesy and navigation. Guenther is an IAG Fellow and chairs the IAG Sub-Commission 4.1 on ‘Alternatives and Backups to GNSS’ and the joint IAG 4.1 and FIG 5.5 Working Group on ‘Ubiquitous Positioning Technologies and Techniques’.

Charles K. Toth is a Research Professor in the Department of Civil, Environmental and Geodetic Engineering, The Ohio State University. He received a M.Sc. in Electrical Engineering and a Ph.D. in Electrical Engineering and Geo-Information Sciences from the Technical University of Budapest, Hungary. His research expertise covers broad areas of spatial information systems, LiDAR, high-resolution imaging, surface extraction, modeling, integrating and calibrating of multi-sensor systems, multi-sensor geospatial data acquisition systems, 2D/3D signal processing, and mobile mapping technologies. He has published over 300 peer-reviewed journal and proceedings papers, and is the co-editor of the widely popular book on LiDAR: Topographic Laser Ranging and Scanning: Principles and Processing. He is
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