A THEORETICAL AND PRACTICAL ANALYSIS OF GNSS BASED ROAD PRICING SYSTEMS, CONSIDERING THE EGNOS/SISNET CONTRIBUTIONS

8-10 December 2004, ESA/ESTEC, Noordwijk, the Netherlands

Benito Úbeda(1), **Rafael Toledo**(1), **Juan Guillerno Jordán**(2) , **Soledad Montes**(2)

(1)***Universidad de Murcia***
Dpto. de Ingeniería de la Información y las Comunicaciones
Facultad de Informática, Campus de Espinardo, 30071,Murcia, Spain.
Email: bubeda@um.es, toledo@um.es

(2)***LISITT, Universidad de Valencia***
Instituto de Robótica,
Aptdo. 2085 4607, Valencia, Spain
Email: jjordan@glup.irobot.uv.es

INTRODUCTION

Nowadays, one of the most important applications of the global navigation systems based on satellite positioning (GNSS) are the road pricing systems. On 29th January 2004, the European Parliament determined tu support the efforts concerning GALILEO, which has become a high infrastructure project. Furthermore, on 24th April 2004, the European Commission issued a European Directive stating the future implementation of a Pan European toll collection system. The eligible technologies for this system will be microwave at 5.8 GHz, GNSS and cellular networks, thus opening a wide market for the development of GNSS systems.

Different toll collection methods are being prepared. All of them rely on an accurate GNSS positioning source, either as the leading positioning information input or as a support system, to measure vehicles movements along roads. The coordinates of the vehicle are then compared to an on-board cartography to determine the amount to be deducted, taking into account the distance travelled, the entries and exits of a road or any other parameters considered. Different pricing approaches are being planned. In order to reduce the complexity of the on-board unit (OBU), the different solutions rely on simplified maps, which consist on areas, corridors and virtual gantries. The toll areas must be distinguished by the OBU, without mistake, since the user will not tolerate any single exceeded euro on his bill.

This paper presents both theoretical and practical conclusions about GNSS-based road-tolling systems, considering the EGNOS/SISNeT contributions, and how an increase of the locked satellites, using the GPS, GLONASS and GALILEO satellite constellations, will affect to the localization solution. The problems that a system based exclusively on GNSS has to deal with will be discussed. Problems such as the lacks of precision and coverage, or the service interruptions due to disturbances on the satellite network, in a million users market where no particular exceptions are possible to treat, are analysed. GNSS lacks of precision and coverage in city environments, tunnels, etc. would bring systematic errors in the vehicle localisation. The synergism of different nature approaches presents a possible solution to our problem with the integration of some of them in a single unit. The EGNOS/SISNeT improvements in precision as a solution to problems such as the parallel roads or on/off operation associated to entrance to highways, are studied. Extensive tests have been carried out and analysed which show the limitations of a system exclusively based on GNSS, and how precision and coverage depend on the number of locked satellites.

Dedicated Short Range Communications (DSRC) is an alternative technology to be taken into account, since it is a mature technology widely proven and implemented. The DSRC solution uses microwave communications so every single entry into a different fee zone must be covered by a DSRC gantry. The costs in hardware infrastructure derived from this solution may refuse its implementation for a wide area system (i.e. covering a whole road network, including minor roads). However, GNSS/CN systems need strict enforcement procedures, which include spot checks. These checks could be accomplished by means of DSRC. Without any doubt, other technologies than GNSS should be used to guarantee the enforcement of the system.

Finally, data fusion from different localization devices such as GNSS, odometer or inertial sensors, is presented as the most reliable choice to guarantee the precision and integrity required in an automated toll collection system.

In order to evaluate the different possibilities, this paper will include the results of the tests made by the Murcia and Valencia universities in a research project funded by the Ministry of Transports and Infrastructures, in the motorway A7 (Mediterranean motorway).

STATE OF THE ART OF ROAD PRICING SYSTEMS

First of all we should talk about what we understand for road pricing systems. This definition comprises the different modes and technologies used to collect tolls for the use of a road infrastructure, but it should not be understood just in its economic sense. Other concepts like control of congestion, accident risk reduction, efficient use of the road and environmental issues are involved. Since road pricing is not just a matter of collecting tolls, some other needs arise, like eliminating artificial barriers and covering the external costs of the road. This can be achieved with automatic systems that enable collecting tolls without having to stop the vehicle, and also allow varying the fees according to concepts like distance, level of congestion, environmental sensitivity of the area, etc.

The first technology enabling electronic fee collection (EFC) was DSRC (Dedicated Short Range Communications). Most countries using EFC deployed DSRC systems that use microwaves at 5.8 GHz, which are currently not fully compatible. The work undertaken by CEN resulted in January 2003 in a set of technical standards for the compatibility of 5.8 GHz, following the adoption of pre-standards in 1997. However, these pre-standards do not cover all the DSRC systems in operation in the Community and encompass two variants which are not totally compatible. Manufacturers have agreed, within the Community, to develop interoperable products based on existing DSRC 5.8 GHz systems.

The Swiss HVF (Heavy Vehicle Fee) system [1][2] was the first using satellite positioning for the operation of EFC. It started to operate on 1 January 2001, and is mainly based on DSRC for border crossing detection and tachograph for distance account. The GNSS unit is used as a redundant source, to prevent and detect fraud. LKW Maut, the german road pricing system [3][4], will be mainly based on GNSS/CN (Global Navigation Satellite Systems / Cellular Networks) technologies. The On Board Units (OBU) will calculate the fee by comparing its position to a database containing the definition of the charge objects. This system was supposed to operate since August 2003 but a great number of problems delayed this date until January 2005. On this date, the system will begin to work with a reduced functionality, and should operate normally from January 2006. Some of the problems of the system dealt to the functionality of the OBUs, which suffered SW and HW problems leading to malfunction and miscalculation of fees.

On the legal side, the EC drafted in 2003 two proposals for European Directives related to road pricing, one of them related to the supporting technologies and the other to the legal framework. The so called 2004/52/EC EFC Directive [5], stated that a single Pan European EFC service should become into operation in 2005 for heavy vehicles and in 2010 for all other vehicles. This EFC service should remove artificial barriers, and be based on DSRC or GNSS/CN technologies, but from 2008 only GNSS/CN technologies would be eligible for new systems. Furthermore, the directive envisaged that DSRC systems should disappear from 2012. Motorway operators (who have invested in DSRC systems so far) opposed to the approval of the directive, which had to be modified by the Commission. In the definitive version (29 April 2004) any explicit reference to an “expiry date” for the microwave systems was deleted. Also the date of start of the Pan European EFC service has been deleted. The supporting technologies will be any or a combination of the following: 5.8 GHz microwaves (DSRC), satellite positioning and mobile communications using GSM-GPRS. Other technologies including digital tachograph will be allowed, on condition that this does not lead to discrimination. The EC continues supporting GNSS, and has included in the Directive the recommendation to use GNSS/CN, although explicitly recognizes that problems could arise with fraud prevention and reliability. The second proposal for Directive, called “charging of heavy goods vehicles for the use of certain infrastructures” [6] was intended as a modification of the “Eurovignette” Directive [7]. This Directive would affect not only the Trans European Network (TEN) but also the parallel competing roads, for all lorries over 3.5 tonnes (as compared with current 12 tonnes lorries). Tolls may vary according to vehicle type, time of day, level of congestion, environmental sensitivity of the area, accident risk and other concepts. The aim was to integrate more effectively external and infrastructure costs. This proposal was not accepted and currently is in process of modification.

Talking about normalisation, ISO and CEN are working on the definition of the prCEN ISO TS 17575 "Application interface definition for CN/GNSS based EFC" [7]. Its main objective is the communication between the OBE and the CE (Central Equipment), defining transactions, SW and data updating of the OBU, and roaming between service providers. Also, some of the data to be used in the charging process is defined, when there is a need to send or receive this data via the CN link. The algorithms for fee calculation are not defined, nor the specific needs of precision or quality of the positioning equipment. The standard is under development and aimed to be completed at the end of 2004. MISTER project (Minimum Interoperability Specification for Tolling on European Roads) is closely related to ISO 17575 which provides a basis for interoperability, but is not sufficient to guarantee interoperability. The objective of MISTER is to define how ISO 17575 should be implemented in Europe to guarantee technical and procedural interoperability. MISTER supports and partially defines the European EFC service required in the EFC directive.

THE GNSS/CN –GIS TESTS

Introduction

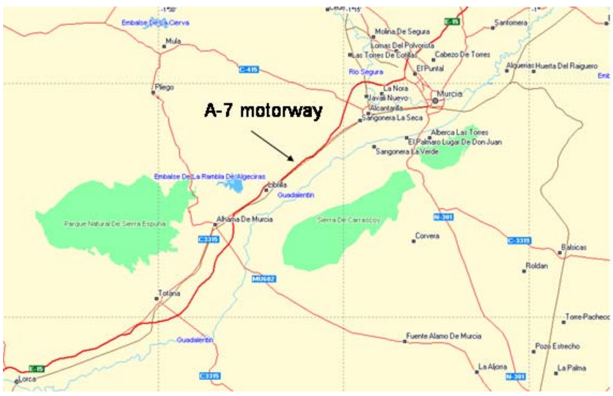
As a part of our research in the ITS area, some real tests have been carried out in the Campus of Espinardo, University of Murcia. Our purpose was to evaluate the technical feasibility of implementing a roadpricing application based on GNSS/SBAS sensors and a GIS database, and the pros and cons this solution presents. For this reason, costs considerations have not been taken.

Two GNSS sensors have been evaluated:

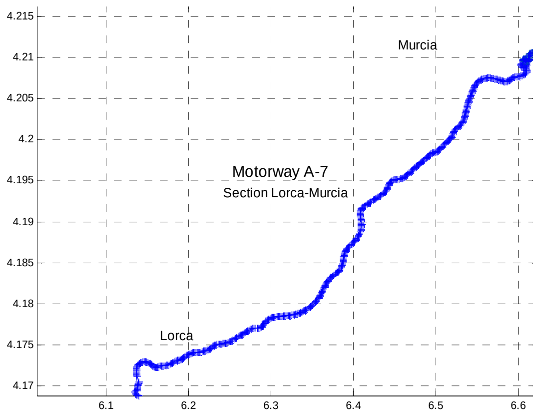
- A GPS/EGNOS Novatel Millenium OEM-3 sensor. This model operates with the RTCA (DO-229) protocol. It is used to send the EGNOS position correction by a GPRS link using the SISNeT application.
- A GPS/GLONASS Thales Navigation GG24 sensor, in order to study the benefits of using a double constellation.

For our tests, we selected the A-7 motorway in the region of Murcia (fig. 1) to study the feasibility of the toll collecting system. A priori, the conditions of the selected motorway offer good SIS availability along the road. A 700 m. tunnel and some crossing motorways over ours are the only sources of disturbances for the GNSS coverage. A complete absence of coverage and random fast fading decrease of the number of satellites (keeping less than four satellites in view in some cases) are the consequences of them respectively.

An unpredicted coverage failure was due to the proximity of high vehicles such as trucks and buses, specially in both vehicles were riding very close. The SIS fading in these situations can be quite deep. For this reason, a proper selection of the optimal location of the GNSS receiver must be carried out.



a) GIS map of the A7 motorway in Murcia.



b) Trajectory in our test

Fig. 1 Selected motorway for out tests. Similarities between the GIS map description and the trajectory obtained with our test vehicle are highly visible.

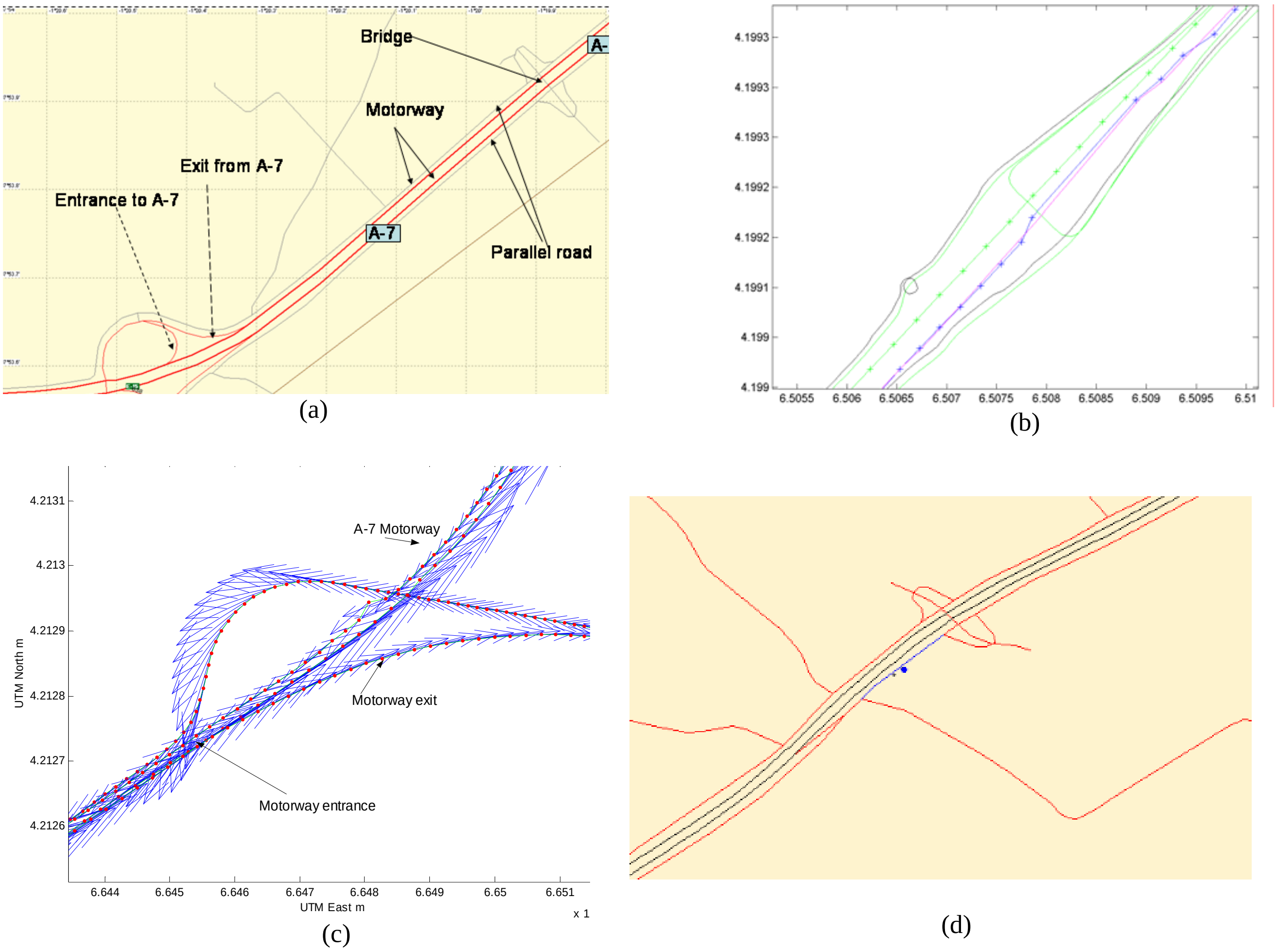


Fig. 2. Parallel motorway and minor road (a,b), exit and entrance in motorway (c) and software application to display and compute the toll (d).

The features of our software application are:

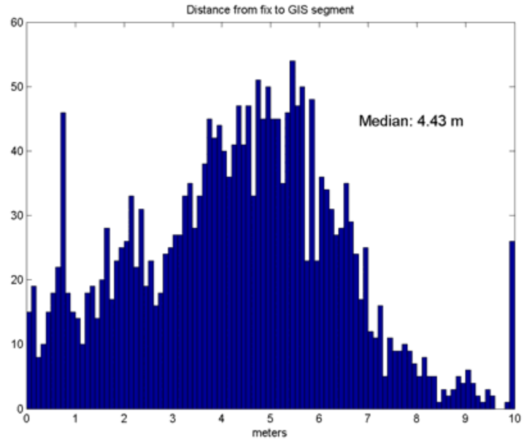
- Communication of the PC with the GNSS receiver by the serial port.
- Location of our vehicle on a Navtech GIS map.
- Remote location thanks to the GPRS link installed.
- Capture of sensor measurements and trajectories.
- Estimation of the distances travelled through the toll chargeable roads. In the tests developed through the A-7 motorway, the GNSS drifts compared with the tachometer information were around 100 m. in 100km.

The on-board unit installed in our vehicle for the GNSS tests consists of a single board computer (SBC), the GNSS sensor (Antenna and OEM) and the GPRS modem. In the tests presented, the GNSS rate output frequency is 1 Hz.

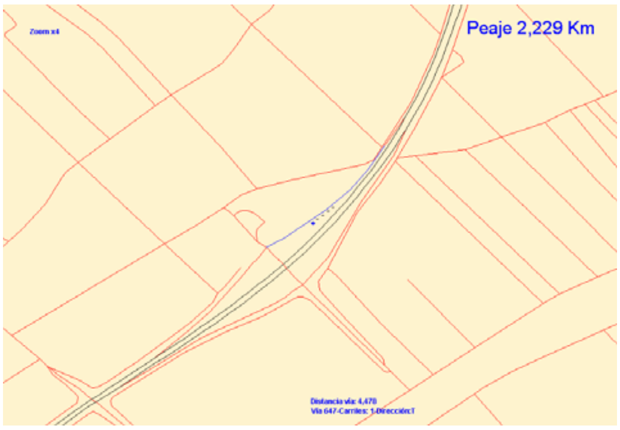
As result of our investigations, the main issues the GNSS navigation has to deal with in a road pricing application are:

- Parallel non-chargeable roadways few meters far from the motorway. In this situations, the precision of the system must be enough to avoid toll collecting detection errors (fig. 2.a and 2.b).
- Right detection of the exits and entrances in a motorway (fig. 2.c)
- Accurate toll distance.
- Aiding systems for tunnels and temporary lacks of coverage.

Fig. 2.d shows a GIS map with the vehicle position superimposed when our vehicle enters in a road non-chargeable road. This is detected by our application, and the toll collection is disabled. In the case of the tunnel, we know the location (the UTM coordinates of the entrance and the exit). This allows us to simply add the length of the tunnel to the travelled distanced and treat it as a virtual gantry.



(a)



(b)

Fig. 3. Histogram for *ds* (a) and user interface (b).

An accurate GIS map is necessary to calculate the distance of the vehicle to the nearest GIS segment (*ds*). Being *U* a developer parameter and an accepted threshold for the position error, when *ds* < *U*, the system understands that the vehicle is located in this roadway segment. In Fig. 3.a we can see the histogram of the *ds* value in a test of 80 Km.

Table I presents GNSS data from seven trajectories along the A-7 motorway and surrounding roadways. Approximately 770 km. have been logged.

Table 1. GNSS/CN test data.

GNSS sensor	Size (epochs)	Travel distance (km.)	Availability (%)
GPS/EGNOS (Novatel)	21716	407	97.6
GPS/GLONASS GG24	19426	363	93.6

The travelled distance has been calculated as the result of adding the GNSS single segments and smoothing the trajectories. To improve the estimation of the travelled distance an smoothing process has been applied to the trajectory. A five seconds moving average has been applied. Fig. 3.b shows the user interface in our roadpricing application. The difference between these values and the distance measurements read by the vehicle tachometer is lower than 1 km.

Our investigations in the use of the GNSS to a road pricing application bring us these main conclusions:

- GNSS availabilities around 90%, do not seem to be enough for the automated road pricing system requirements.
- EGNOS by geo sat IOR (PRN 131) has low coverage in the south of Spain.
- EGNOS by SISNeT is not a valid solution today due to the lack of a guaranteed real time data through the GPRS modem.
- The increase of the number of satellites by using the GLONASS/GPS is not profitable in motorways.
- Interpolations and smoothing methods for GNSS trajectories, is an accurate way to estimate the distance.
- The GNSS/GIS accuracy is enough to distinguish between parallel roadways separated ten meters (considering the distance between roads as the distance between their central lines).

A PILOT APPLICATION FOR A ROAD PRICING SYSTEM

A pilot road pricing application was designed and implemented based on a subset of the specifications of the ISO 17575. The main concern was to test the ability of the application to detect the different charge objects as the vehicle moves, and to calculate correctly the fees. Different scenarios according to ISO 17575 were designed, including a zone scenario, a corridor scenario, and a virtual gantry scenario. These are the charge objects defined in the standard, each one focusing on a different toll mode. The application was tested with each kind of scenario, enabling us to identify the main pros and cons of each solution. An important consideration for us was to evaluate the feasibility of a low cost on board system. In other words, would it make sense to implement a road pricing system based only on a GNSS position source? Is there a real need to include odometer or inertial systems? And concerning the memory and communication needs, could be feasible an on board system which relies on a small database including just the geographic objects or is it mandatory to use a complete database including all the roads?

Three different types of scenarios were designed, which are intended for specific types of tests, as follows:

- A zone based scenario in the metropolitan area of Valencia. This scenario is intended for distance charging into the zone. Tests should show whether distance charging is possible relying only on GPS.
- Corridor based scenarios in CV-35 road and AP-7 motorway. Tests cover detection of entrance and exit of the corridor, variation of width and number of points of the corridors and distance charging.
- Virtual gantry based scenarios in CV-35 road and AP-7 motorway. Tests cover detection of the virtual gantry.

The first set of tests carried out involves the study of the application efficiency in detecting the charging objects. Tests comprising virtual gantry based scenarios have shown a succesful detection of the crossing in the 100 per cent of the cases. Tests involving corridor based scenarios have shown the dependence on the width of the corridor, and the radius at the entry points. Radius should be at least 20 meters to ensure detection of speeds up to 150 Km/h. However, still the 3.6 per cent of the tests have failed on detection using 20 meters radius. This error is cancelled when using 30 meter radius. Considering width, over 90 per cent of the tests have been correctly detected using 15 meters of width, and over 98 per cent using 20 meters. In both scenarios, no misdetection has been obtained due to parallel or crossing roads.

When GPS is used for distance charging, two different situations can be considered, concerning the visibility of satellites. At roads, where no buildings obstruct the GPS signal, typical errors of 1.9% have been obtained, reaching a maximum error of 6.6%. The second situation occurs in cities, where direct vision of any satellite is hard to achieve. In that case, the averaged error rises to 5.9%, and the maximum error to 16.7%. In addition, an error in distance measurement has been found when corridor based scenarios are used, due to the uncertainty of distance covered within the corridor at the entrance and the exit. The maximum variation obtained in the tests has been 48 meters.

Additionally, an estimation of the memory needed to allocate all the charging objects of a whole province has been calculated. The main highways within the province of Valencia and the border of the city of Valencia have been considered. Simplified definitions of the charging objects according to ISO 17575 have been used in order to minimize the memory needed. The estimated sizes of the corresponding charging objects result as follows:

- A 9.5 Kbytes zone scenario to define the city of Valencia.
- A 21 Kbytes set of corridor scenarios to define the main highways.
- A 10 Kbytes set of virtual gantry scenarios to define the main highways.

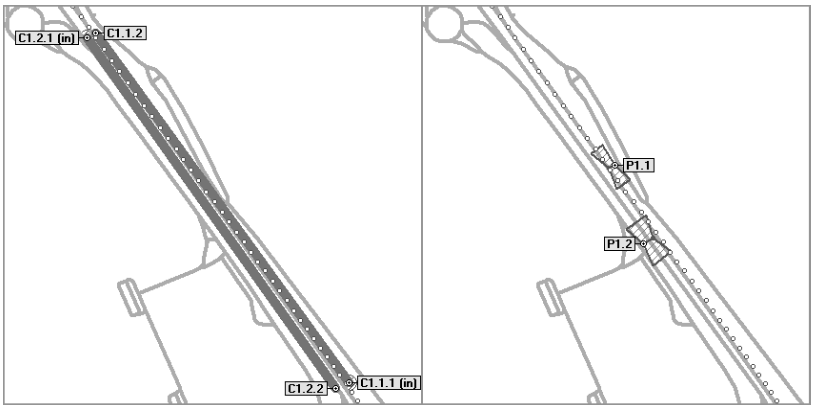


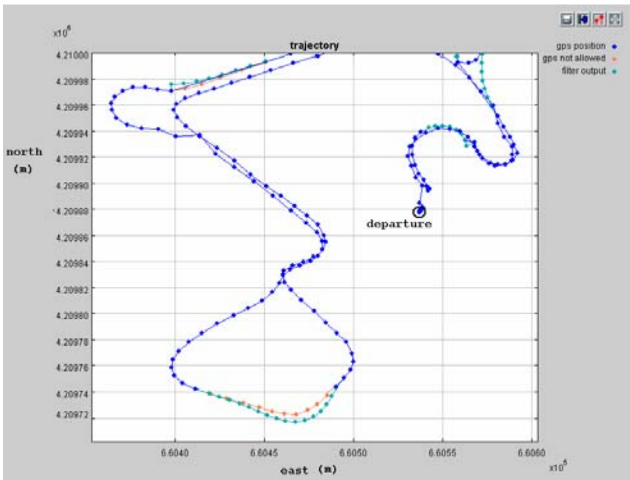
Fig. 4. Two scenarios in CV-35 road: corridor based and virtual gantry based.

A part of the work done has been focused on the study of charge objects defined in the standard ISO 17575. The use of corridor based scenarios is suitable for distance charging. It has been shown that an error exists when only GNSS is used, so the use of other position sources (odometer/INS/tachograph) is strongly recommended. Despite in major roads this could be carried out with GNSS and cartography, errors obtained in city scenarios are too large to rely just on GNSS. Another main drawback of using corridors is the adaptability to the shape of the road. Detection is localized at the entry of the corridor, thus if no entry has been detected, no tracking through the rest of the corridor would be done. In addition, entries are defined by circles, which do not fit the shape of the road, and critic areas must be defined to avoid parallel roads, crossings and tunnels. Virtual gantry based scenarios cannot be used to measure distances (the corresponding distance must be fixed previously), but adapt easier to the form of the road. A suitable location and shape can be chosen along the stretch far away from critic areas. Furthermore, virtual gantries can provide an easier compatibility with existing DSRC systems. The main drawback lays on the fact that the detection of the whole stretch is localized in a short area. Finally, regarding to memory needs, even although a virtual gantry must be defined between each entry and exit, the memory needed is less than the one needed in a corridor based scenario.

INTEGRATION WITH INS/ODOMETRY

The lack of GNSS coverage in some environments (even when SISNeT signal is used) is a real problem that cannot be solved with a global positioning system. A reliable solution for these periods without GPS signal is absolutely required to guarantee the system success. Both odometry and inertial measurements have been studied to determine the best way to fulfill the system requirements. The nature of the inertial measurements (accelerations and rates of turn in the three coordinated axes of the body frame) complements perfectly the deficiencies of localization systems based on the GPS solution. However, the need of a double integration process to obtain the position from the acceleration measures is the principal source of error in an INS/GPS integrated system. Often updates should be taken to zero the solution drift. The odometry option avoids the double integration, but problems such as glides, uncertainty of the effective wheelbase, unequal wheel diameters, etc. encourage us to think about some other option. In our approach, error models have been implemented in order to remove bias deviation from the inertial measurements. To estimate the quality of these models a test with no forces applied to the vehicle (except the assumption of the Earth's gravity) was carried out with a Crossbow VG-600 vertical gyro, which provides the accelerations and the rates of turn in the three coordinated axes of the body frame. When error models had not been used, the position drifted quite soon, becoming –55 m. in 60 seconds without aided updates. When an exponential approximation was implemented (see [9] for details) the position was retained under 70 cm. during the same 60 seconds without any aided update. These results invited us to implement an GNSS/INS integrated navigation system. To fuse the GNSS and the INS measurements, an integration architecture based on an Extended Kalman Filter has been implemented (see 10 for details). Next, how the GNSS/INS integrated system improve the quality of the solution is shown.

(a)



(b)

Fig. 5. A typical situation where the GNSS/INS solution is recommendable (a), and the INS solution when GPS has no coverage (b).

Fig.5.a shows a difficult situation on a Spanish roadway. In this situation, the GPS constellation does not offer positioning, and some other options such as DSRC gantries are perforce rejected. Fig 5.b shows how our GNSS/INS integrated systems deal with these situations. A fragment of a trajectory in our campus, where the trees and the

buildings block the GPS signal is shown. In the left part of the plot, the GPS positioning disappears and the INS solution maintains positioning information updated. In the right part of the plot, some experiments are carried out disabling the GPS signal. Similar results are obtained. Taking into account that the GPS receiver output frequency is 1 Hz., we can easily see the inertial navigation system estimating reliable positioning during 10 seconds (lowest part of the plot). In some tests developed in the Campus de Espinardo of the University of Murcia, where the GPS signal was disabled during periods of time, average position errors were 6sec.–10m., 10sec.–15m. and 15sec.–20m.

One of the main disadvantages of working with INS technology is its price, practically not affordable if we think about on-board-units for vehicles. However, the fast development of the MEM's devices (based on microelectromechanical technology), with real low cost price units (few dollars the set of inertial sensors), encourage us to believe that the future on-board-units for toll-collecting systems will implement inertial technology in the main aiding positioning system of the GNSS.

CONCLUSIONS

The Global Navigation Satellite Systems are presented as an useful tool to develop road pricing systems. The application of the cellular network technology to the GNSS, the GNSS/CN systems, enhances the quality of this GNSS solution. According to our tests, the EGNOS system is able to improve the precision of the positioning, avoiding the accuracy problems. The SISNeT system, a broadcast correction position sent by GPRS, could be a practical solution when the geostationary satellite is out of view, but the deficiencies of the GPRS link diminish its potential benefits. According to our research, the GNSS/CN solution does not fulfill all the requirements demanded by a reliable, robust, integrity automated toll collecting system, and the increase of the number of satellites in view, achieved by the use of a GLONASS/GPS receiver, can not deal with the lacks of a GNSS/CN system. These conclusions encourage us to work on a complementary solution, based on different nature sensors. Aiding system based on DSRC gantries, virtual gantries, INS navigation and odometry sensors have been studied in this work, selected results have been presented and the benefits of their implementation on the navigation system of the vehicle have been proven. Finally, our GNSS/CN/INS integrated navigation system is presented as a reliable, high integrity solution for the positioning requirements connected with a road pricing system implementation.

AKNOWLEDGEMENTS

The Authors would like to thank the Spanish Fundación Séneca, Agencia de Ciencia y Tecnología de la Región de Murcia, for founding this work under the grants PI-78/00833/FS/01 and FPI02-00001/EFPI/04 and the Spanish Ministerio de Fomento for sponsoring the research activities.

REFERENCES

[1] Swiss HVF system. http://www.are.admin.ch/are/en/verkehr/lsva
[2] Fela. HVF technical description. http://www.fela.ch/elektroniktelem/en/hvf/index.html
[3] LKW Maut system. http://www.bmvbw.de/lkw-maut-.720.htm
[4] Toll Collect. http://www.toll-collect.de
[5] Directive 2004/52/EC of the European Parliament and of the Council of 29 April 2004 on the interoperability of electronic road toll systems in the Community
[6] Proposal 2003/0175 for a Directive of the European Parliament and of the Council amending Directive 1999/62/EC on the charging of heavy goods vehicles for the use of certain infrastructures
[7] Directive 1999/62/EC of the European Parliament and of the Council of 17 June 1999 on the charging of heavy goods vehicles for the use of certain infrastructures
[8] ISO TC204 / SC5 / WG5, CEN TC278 / WG1 prCEN ISO TS 17575. Road Transport and Traffic Telematics - Electronic Fee Collection (EFC) - Application interface definition for CN/GNSS based EFC.
[9] Billur Barshan and Hugh F. Durrant-Whyte. Inertial Navigation System for Mobile Robots. *IEEE Transactions on Robotics and Automation, Vol. II, No. 3.* 1995.
[10] Rafael Toledo, Miguel A. Zamora, Benito Úbeda and Antonio F. Gómez-Skarmeta. An Integrity Navigation System based on GNSS/INS for Remote Services Implementation in Terrestrial Vehicles. *2004 IEEE Intelligent Transportation Systems Conference Washington, D.C., USA, October 3-6, 2004. pages: 477- 480.*