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CONTRIBUTION OF HYBRIDIZATION TO THE PERFORMANCE OF SATELLITE NAVIGATION SYSTEMS

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ABSTRACT - *For a navigation system to be declared as usable for civil aviation purposes, it must fulfil some normalized requirements in a given phase of flight. To date, no current satellite navigation system alone can satisfy the demanding civil aviation requirements. This lack of performance makes the hybridization necessary between the satellite system and another (other) system(s). The aim of this paper is to evaluate the contribution of hybridization to the performance of the main navigation systems, and in particular satellite systems such as GPS and GNSS. The interesting case of INS hybridization will be emphasized.*

1 - INTRODUCTION

The advent of digital circuits and satellites permitted to air navigation to enter a new era. Digital communications and satellite navigation represent in fact the main foundations of new concepts of air navigation. Within this context, the ICAO has defined in 1991 the CNS/ATM concept in order to develop satellite-based systems, capable to resolve navigation problems such as traffic congestion, non-continental area coverage and HF voice communications. In this way, three objectives are to be reached : accurate navigation according to RNP criteria using among others satellite systems, efficient air traffic surveillance by means of S Mode Secondary Surveillance Radar (SSR) and Automatic Dependence Surveillance, and reliable air-ground data link by means of VHF Data Link, INMARSAT Aeronautical Mobile Satellite Services, S Mode SSR or Aeronautical Telecommunications Network. In this paper, only the navigation aspect is analysed.

The navigation domain offers a large scale of systems (or means) of navigation characterized by the data type they provide, the rate these data are generated, the accuracy of data and its dependence on time and space, etc. Current criteria adopted to classify navigation systems mainly depend on :

- whether the system makes angle, propagation delay or time difference measurements,
- whether or not the navigation is of a dead-reckoning type,
- the carrier frequency used and the range guaranteed, when the navigation procedure is based on electromagnetic wave propagation,
- the phase of flight they are concerned in.

On the other hand, to ensure safe aircraft operation, the ICAO has established for each phase of flight the navigation performance requirements to be met by the selected system of navigation. These requirements result from the Required Navigation Performance (RNP) concept and are expressed in terms of accuracy, integrity, availability and continuity of service. Definitions and critical values were published first in [ICA94], and derived for Global Navigation Satellite Systems (GNSS) in [ICA97].

Navigation by satellites offers indisputable benefits mainly in terms of coverage, accuracy and equipment complexity. As for nav aids, a given satellite navigation system to be considered must fulfil the corresponding requirements. To date, however, no existing satellite navigation system, if considered alone, meet the demanding requirements. It is then necessary to hybridize the satellite navigation system with another (or other) system(s).

In the following, the second section recalls the context of the hybridization, provides some elements to characterize it, lists some examples and summarize the major techniques used. The third section proposes a hybridization schemes layout in three groups. Thereby, a satellite navigation system can be coupled with an onboard system (Inertial Navigation System (INS), Barometric altimeter, etc.) and/or a ground system (LORAN-C, pseudolites, etc.) and/or another satellite system (GPS, GLONASS, Geostationary overlay, etc.). Contributions of hybridization on accuracy, integrity, availability and continuity are qualitatively evaluated. In the fourth section, the particular case of INS / satellite system hybridization which improves navigation performance in disturbed environments is considered.

2 - HYBRIDIZATION : CONTEXT, EXAMPLES AND TECHNIQUES

For a navigation system to be declared as usable for civil aviation purposes, it must fulfil some normalized requirements in a given phase of flight, with satisfactory effectiveness on cost and complexity. However, a given system of navigation considered alone can not meet all the desirable requirements as illustrated in Table I.

System or means	Strong points	Weak points	type of information
GPS, GLONASS	Accuracy, coverage	Integrity, continuity, RF interference high dynamics ?	3D position and velocity Time
INS	Short term accuracy (stability), immunity from perturbations	Error drift, cost, high dynamics ?	3D position and velocity Attitude
ILS, MLS	Availability, integrity, accuracy RF interference	cost, multipath	azimuth, elevation, range
VOR, DME	Reliability (LOS propagation), low user equipment cost	Short range	Relative angle, range
Doppler Radar	Reliability	Error drift	3D velocity, 2D position
Barometric altimeter	Self-contained	Accuracy in high vertical dynamics	Vertical data
LORAN-C	Long range	Accuracy, coverage	2D position (long., lat.)

Table I Characteristics of some systems of navigation

It is thus necessary to hybridize two or more systems of navigation in order to obtain suitable performance. This hybridization has to take advantage of complementarity and/or redundancy of these systems while maintaining equipment cost and complexity optimized. To this end, design questions about system compatibility (operation principle, working frame, etc) and hybridization level to perform (quantities to aid, loosely or tightly) must be resolved. As an end result, a good hybrid system must show an improved performance in comparison with that of each system considered alone.

Numerous schemes of hybridization have been implemented and their analyses published. Their large range variety makes somewhat difficult to list and classify the existing schemes in an exhaustive manner. However, to have a brief overview on the field, some factors must be taken into account :

- a- the capability of a system to perform lonely the navigation function with a given performance : e.g. GNSS, INS or LORAN-C are self-contained systems while VOR, DME, or Barometric altimeter data must be completed to yield 3D position of the aircraft.
- b- the level of hybridization which is low when integrating loosely, and high when integrating tightly. This level is closely related to the degrees of redundancy and complementarity induced by such integration. For example, the fact that integration takes into account raw data or output navigation solution corresponds to the choice of high or low hybridization level, respectively. The hybridization can then consist of an open loop or a closed loop operation.
- c- the information to be aided (position and/or velocity and/or attitude) and its form (absolute or differential).

In Table II, examples of the main hybridization realisations and corresponding expected improvements are given.

	Integrated system	Result of the hybridization, improved parameter
1	GPS / INS	Integrity, resistance from perturbations
	GPS / Baro	Vertical accuracy
	INS / Baro	Vertical accuracy
	GPS / INS / Baro	Accuracy, integrity
2	GPS / Pseudolite	Coverage, accuracy
	GPS / VOR/DME	Redundancy of range measurements
	GPS / LORAN-C	Accuracy of en route navigation
	INS / VOR/DME	Accuracy
3	GPS / GLONASS	Availability, continuity, integrity
	GPS / INMARSAT	Accuracy, availability, integrity

Table II Examples of hybridization

Techniques of hybridization

Commercial aircraft currently make use of multisensor navigation systems. The navigation function in FMS exploits the data available from the implemented sensors as VOR, DME, INS and now from GPS, to provide the

most accurate aircraft position. Considering GPS/INS hybridization, main implementation schemes adopted onboard consist in providing navigation solutions of GPS and INS to FMS, performing tight GPS/INS before giving solution to FMS, or performing this tight integration by the FMS (cf. e.g. [McD95]).

Techniques of hybridization implemented in existing multisensor systems consist essentially of linear filtering. They can be classified according to their complexity :

- techniques of low complexity such as a data (re)initialisation or averaging. The possible advantage in some of these techniques is that errors of one system do not affect the other system.
- techniques of relatively high complexity such as maximum likelihood estimation, least squares estimation, mean squares error minimisation and (extended) Kalman filtering. With these techniques, optimality and adaptivity can be obtained. Depending on the selected level of hybridization (loose or tight), integration will result in more or less complex implementation.

In the scope of linear-gaussian problems, Kalman filter remains an optimal tool of hybridization. It provides an optimum estimate of navigation system errors and minimises the increase of errors on position, velocity and attitude. The main schemes implemented consist of one of the following structures : a simple structure of one or two Kalman filters (for tight and loose integration respectively), a bank of Kalman filters where each filter is assigned to a measured pseudorange in conjunction with INS measurements (cf. [YOU97]), or a hierarchic structure of Kalman filters which improves fault detection/isolation and reconfiguration capabilities of the hybrid system [McM93].

However, out of this scope, i.e. when linear-gaussian approximation is not any more satisfactory, the non-linear filtering alternative solution can be adopted [DIM98, CAR97].

In the particular case of GPS/INS integration, fault detection and exclusion algorithms based on least squares estimation, and on sequential analysis theory are used to improve the system integrity monitoring (cf. §4).

3 - SCHEMES OF HYBRIDIZATION IN THE GNSS CONTEXT

As mentioned in Table II, different types of hybridization can be adopted, considering onboard, ground-based or satellite-based systems.

GNSS Hybridization with onboard systems

Systems involved here are the self-contained sensors such as barometric altimeter, Doppler Radar, INS and GPS (or GNSS). In §2, we have emphasized some features of these navigation systems.

An important self-contained system which is widely considered in the following is the INS. Before taking on a brief review of the common integrated systems, it is useful to recall the limitations its use induces. Indeed, due to the feedback gravity correction, inertial navigation solution presents Schuler oscillation (about 84 min. per period) on azimuth and exponential instability (about 10 min. constant time) on the vertical channel. Moreover, the behaviour of this solution depends on drifts, biases and scale factors of inertial instruments (accelerometers and gyroscopes). As a consequence, INS alone can not ensure sufficient positioning performance for long flights.

Baro/INS hybridization constitutes a first solution to the INS problem. The integrated system permits indeed to remove the instability of the INS vertical channel. One common implementation consists in modelling this system with a Kalman filter, where the Baro altitude information, suitably weighted, affects INS vertical position, velocity and acceleration. The efficiency of this integration depends mainly on the fitness of error models to real error sources and on the choice of the parameters values. Reference [WIN80] proposes nominal values of these parameters.

The present time solution consists in combining GPS (or GNSS) and INS. Integrated GPS/INS system can provide accurate and continuous navigation where GPS helps INS to perform (re)alignment , while INS helps GPS to speed-up (re)acquisition, to increase resistance from RF interference and improve integrity monitoring availability in case of satellite masking or in presence of satellite failure. Considering cost aspect, GPS aiding in a GPS/INS integration offers the possibility, if appropriate updating rate is selected, to retain a low accuracy -and then low cost- INS which could be sufficient to provide acceptable performance. Furthermore, GPS/INS integration often assumes the presence of a barometric altimeter to improve vertical accuracy. Considering implementation aspect onboard in a GNSS1 context, one can envisage to systematically integrate the GPS/INS hybridization in the FMS module. Further details on the GPS/INS hybridization are given in §4.

GNSS Hybridization with ground-based systems

GPS augmentation by pseudolite(s) is known to be a promising solution to improve the navigation performance in precision phases of flight. Nominally implemented in pairs, pseudolites (PLs) provide supplementary pseudorange-type (or carrier measurements) information which improves navigation performance in landing approaches. Hence,

centimeter level accuracy is obtained by using DGPS positioning based on carrier phase measurements, where the presence of PLs permits to experience a large change of geometry which helps integer ambiguity resolution algorithms. Simulation results in [MAC97] show a benefit on the time of convergence of two algorithms in using one or two pseudolites. Integrity is also improved in terms of fault detection and isolation rates. Furthermore, better geometry obtained with PLs leads to lower DOPs, and particularly to lower VDOP which is appreciated during a precision approach. However, GPS/PL integration can induce problems of synchronisation between PL clock and satellite time and of a possible interference due to the PL signal power. By selecting suitable PL implementation configurations and tuning the PL transmission power and/or the carrier position the effects of these problems can be minimised (cf. [PAR96,COB98]). Furthermore, differential delays induced by tropospheric propagation when using LP paths can be greater than that resulted when using satellite paths, and then must be corrected (cf. [BAR96]). Moreover, for GPS/PL reliability, PL data rate and transmitted message content are of importance. Also, a higher complexity due to PL augmentation should be noted. Indeed, positioning solution with PL necessitates a second order linearization in comparison with the first order approximation used with GPS alone. Finally, the integrated GPS/PL system remains subject to RF interference.

PL implementation is planned to complement a local area DGPS (LADGPS) to allow pilots to perform Cat. II/III precision landings through a primary means of navigation. LADGPS consists in fact of a reference station to elaborate differential corrections and a monitoring station which generates an integrity information based on error estimation of its position. These messages are then broadcast by direct VHF Data Link to users. Using carrier phase-based positioning, LADGPS complemented by PL would satisfy, if robustness is proven, precision approaches requirements.

Another system which enters in this scope is GPS/LORAN-C. This integrated system represents in fact a reliable navigation system for oceanic and continental navigation : GPS offers accuracy and coverage while LORAN-C provides positioning solution in case of GPS failure. Benefit assessments of the GPS/LORAN-C integration are widely published. For example, in [KUG96] integration through raw data least squares filtering improves availability and integrity, while in [DYK96] augmentation of GPS by LORAN-C and a barometric altimeter is applied to non precision approaches, where substantial improvement on the system availability is obtained. GPS/LORAN-C represents a good solution for short term, but in a perspective to establish a satellite-based system of navigation for all phases of flight, ground-based navigation aids such as VOR, DME and LORAN-C would tend to disappear.

GNSS Hybridization with satellite-based systems

Other satellite systems can help GPS-based navigation system to build-up a GNSS1 system. For the moment, INMARSAT and GLONASS satellites candidate to this hybridization.

With sufficient constellation, GLONASS is proved, through several published results based on measurements, to offer similar performance to that obtained by GPS when selective availability is off. The integrated GPS/GLONASS system can take advantage of the higher satellite redundancy by providing supplementary measurements which increases the positioning accuracy and integrity. Structural inadequacy between reference systems of GPS and GLONASS is shown to be overcome through transformation methods using e.g. least squares estimation [MIS96]. Furthermore, a recent work [HEI97] indicated positive results about the use of carrier phase measurements for a possible GPS/GLONASS positioning, despite the difference of frequencies used by GLONASS transmission. All these results permit to present GPS/GLONASS integration as an attractive solution. Nevertheless, current poor GLONASS constellation and mentioned inconsistencies on GLONASS information [COO97] attenuate the certainty that GPS/GLONASS integration will be retained in the GNSS system.

The first phase of GNSS - called GNSS1 - is planned to satisfy the RNP of a primary means of navigation for phases of flight down to Cat. I precision approach. GNSS1 is now in an advanced step with the launched regional programs : the american WAAS program, the european EGNOS program and the Japanese MTSAT program. Based on a Wide Area DGPS concept, these programs expect to use a ground-based station networks and geostationary satellites (GEOs). The ground stations will monitor GPS and GLONASS constellations, generate integrity messages and differential corrections, and elaborate navigation message for GEO satellites. These messages are sent to GEO satellites which rebroadcast them on the L1 frequency toward users. Availability is then improved since users receive a supplementary pseudorange-like information from GEOs. It should be noted that these benefits brought by the GEO augmentation are reduced when approaching the poles because of the poor coverage of GEOs at high latitudes.

The future GNSS2 system has in prospect to reach the sole means capability for all phases of flight. For this end, and if GPS and GLONASS remain under military control, a new civil satellite navigation system will be designed and implemented. Based on other satellite constellations such as Inclined Geosynchronous Orbit (IGSO) or Low Earth Orbit (LEO) constellations, this new system would logically become in a first step the primary means of

navigation. Also, the development of this system should take advantage of technical results obtained for GPS and GLONASS. GNSS2 will with no doubt represent an integrated super-system.

Other hybridization schemes

Although our interest is on the future schemes of hybridization, we would like to emphasize the well-established VOR/DME/INS integration scheme. It is indeed a proven scheme which has been subject of numerous studies. This hybridization inevitably provides an improved accuracy in comparison with that obtained by VOR/DME. Optimal filtering of VOR/DME and INS data permits an INS 'auto-calibration' by means of the output estimated INS errors. A detailed example using a maximum likelihood filter is given in [BOB73]. As for in GPS/INS integration case, a low cost INS can be satisfying if sufficiently high updating is applied by the VOR/DME subsystem. Moreover, INS in-flight alignment can be achieved by VOR/DME.

In a more general context, the complementarity of INS and radio aids improves availability, integrity and continuity since the INS data remain available particularly in case of radio aids updating outages.

4 - INS / GPS (GNSS) HYBRIDIZATION

No current satellite system to date can ensure the navigation sole means functionality because of the lack of integrity, continuity and resistance from RF interference, particularly in the most demanding phases of flight. The interesting hybridization of GPS (position and velocity fixing satellite system) and INS (dead reckoning system) seems then to be unavoidable. Promising performance of this hybridization, through appropriate algorithms, permits to expect its use in a GNSS system.

The benefits of coupling GPS and INS have been widely emphasized and are now identified. Two main objectives are expected when adopting GPS/INS integration: robustness in disturbed environment or in high dynamic situations, and enhanced integrity monitoring. As mentioned in §2, implementation of this integration is currently performed using Kalman filters. For simple implementations, one Kalman filter is retained for tight integration, and two Kalman filters for loose integration. Various integration schemes have been proposed in the literature, e.g. [DA97, PAI95, WOL96, TCH96, LON96, COX78]. More complex implementation schemes can be adopted to improve the integrity monitoring strategy [YOU97, McM93]. In the following paragraphs, used solutions to achieve the two mentioned objectives are presented.

An interesting tight GPS/INS hybridization technique consists of velocity -or range rate- aiding where INS velocity measurements are used to help GPS loops tracking. This can induce a reduction on the acquisition threshold. Indeed, a high quality (negligible acceleration error) velocity aiding permits to reduce loop bandwidth, and then improves the receiver resistance to RF interference. The GPS availability is thus improved in disturbed environment. However, navigation with a too narrow loop bandwidth receiver can fail in high dynamic situations. With such bandwidths, the response time of the system is indeed increased (cf. [UPA82]). On the other hand, in the absence of extra RF interference, an acceleration error induced by the velocity aiding involves an increase of the loop bandwidth which imposes a higher signal-to-noise ratio threshold for the acquisition loop (cf. [CAR77]). As a consequence, care must be taken in interpreting results when velocity aiding is considered, and in some cases a trade-off between tolerated noise and accepted dynamics would be sought while keeping system stability maintained (cf. [JWO96]).

Integrity monitoring for a stand-alone GPS use is currently performed using the RAIM (Receiver Autonomous Integrity Monitoring) algorithm [BRO92]. For a satellite constellation where geometry provides enough information redundancy, this algorithm makes use of a least squares criterion, built on the basis of error residuals of current measurements, to check the integrity of the navigation solution. The quality of such geometry is evaluated through the Approximated Radial error Protection (ARP) method. Limitation of the so called 'snapshot algorithm' arise when measurements affected by a soft GPS failure might contaminate INS during calibration before the failure is detected. Improvements of this algorithm have been proposed through the Autonomous Integrity Monitor Extrapolator (AIME) [LIT95, DIE95] or using sequential algorithms [NIK96, YOU97,98]. The AIME method consists in storing GPS data on a time interval in order to bound the pseudorange error change, and then in averaging on this interval uncorrelated least squares residuals. This can provide enhanced capability of the failure detection.

Based on multi-hypotheses test theory, sequential algorithms check integrity of the navigation solution using all past and current measurements. A loosely coupled GPS/INS scheme based on a cumulative sum (CUSUM) algorithm has been analysed in [YOU97]. Results showed good concordance between theoretical and practical values of detection and isolation mean delays. In [YOU98] simulation results show superiority of sequential RAIM over snapshot RAIM in terms of fault detection availability, for different constellation configurations (including or not geostationary satellites).

5 - CONCLUSION

This brief overview emphasizes the importance of hybridization for navigation systems, and the great variety of implementation schemes adopted according to the types of sensors and for the needed requirements. Representative examples for each class of sensors are provided.

The vulnerability vis-à-vis the RF interference of GPS reception and the lack of integrity of GPS navigation solution naturally impose a coupling with an INS. Good performance of the hybrid system necessitate a judicious choice of the integration level, the integrity monitoring strategy and of the update period of the INS.

Current research in the GNSS context tends to exploit hybridization of different type systems in order to ensure the specified requirements.

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