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DATA FUSION BASED NAVIGATION CONCEPT FOR LEO SATELLITES

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ABSTRACT

The research project[*] presented in this paper deals with novel techniques for a autonomous navigation system for low-earth orbiting spacecraft. The proposed concept is based on an integrated GLONASS/GPS *receiver* as primary equipment for *nominal* operation. *Backup* navigation is based on the onboard measurement of the *geomagnetic field* and real-time processing of *landmark images* delivered by a payload earth observation camera. The paper presents results which have been derived for the TUD-Satellite demonstration mission “Traffic Eye” as application reference. The paper gives a short overview of the overall system architecture and different filtering options. Further, performance results of orbit and attitude determination verified by simulations for GLONASS/GPS, magnetometer and landmark navigation will be presented. The paper gives also simulation results for the fusion of magnetometer and landmark measurements for the navigation and for the determination of systematic errors of landmark navigation in nominal operation mode

1. INTRODUCTION

The research project presented in this paper deals with novel concepts for the cost optimized realization of the mission critical function named “*onboard navigation*” for LEO-satellites. This function is in charge of the autonomous (i.e. without ground support) determination of the instantaneous spacecraft orbital *position* and *attitude*. A reliable and accurate provision of this information is mandatory for the basic tasks of spacecraft attitude stabilization and control, spacecraft orbit control (as subtask of network constellation maintenance) as well as for the general payload management (communication, earth observation, etc.).

Conventional implementations of the navigation function use specific equipment for each sub-function (position, attitude) and *explicit hardware redundancy* (i.e. at least 2 identical hardware devices) to cope with equipment failures. These concepts offer the best performances in terms of accuracy, availability and operational freedom, but suffer from high overall cost in terms of monetary value, electrical power, mass, space, testing and engineering effort.

The objective of the novel approach is to *reduce* the *overall cost* for the realization of the navigation function (see above) by a *reduction* of *the total number of hardware devices* (⇒ *minimum hardware approach*) and *substitution* of hardware functions and hardware redundancy by *advanced data processing techniques* (⇒ *information fusion*).

The approach is based on the *“maximum-use principle”* of any onboard equipment, i.e.

(1) use of any single navigation specific equipment for both position and attitude determination, e.g. GPS receiver, magnetometers

(2) use of secondary equipment, originally not assigned for navigation purposes, e.g. earth observation cameras (optical secondary payloads may be interesting for LEO communication satellites, because they can provide an additional information which can be distributed on a commercial basis by the network owners).

Principle (P1) supports effectively the hardware minimization for nominal operation (only *one* single primary navigation equipment is used, e.g. GPS). To cope with failures of the primary navigation equipment, the combination of principles (P1) and (P2) creates the attractive potential of *functional redundancy*. In such a case a combination of secondary sensors (cheap / simple / reliable / available) and advanced data processing will *substitute* the primary equipment. In the proposed concept the backup navigation relies then completely on the fusion of geomagnetic and image based measurements.

Key topics of a joint research project, which investigates the capabilities and potentials of such a navigation concept, are the development of the appropriate methods and algorithms to realize such a minimum hardware system. These include research activities in the following areas: GPS/GLONASS based navigation (using novel Russian receiver technology),

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magnetometer based navigation, landmark navigation principles, landmark feature recognition, real-time landmark image processing, robust information fusion techniques for heterogeneous error characteristics of measurement, optimized observation strategies taking into account cloud cover of the earth surface, analysis of satellite network constellation performances.

2. NAVIGATION CONCEPT

The onboard equipment of the minimum hardware navigation system comprises the following devices (see Figure 1):

(A) One integrated *GPS/GLONASS receiver* which acts as the sole device for the determination of both position and attitude of the satellite in the nominal mode of operation;

(B) One *3-axes magnetometer* used as a highly reliable backup device for coarse estimation of position and attitude at any moment of time with arbitrary initial conditions for the estimated parameters;

(C) One *Earth Observation (EO) camera* used as a payload device (including the payload specific image processing software) and available for more accurate estimation (in comparison with magnetometer) of position (and possibly attitude), whose operation is restricted by both environmental factors such as illumination, type of terrain, clouds and non-availability for navigation tasks because of earth observation tasks.

(D) Two redundant *onboard computers* which have to run the estimation and fusion algorithms as well as some image processing algorithms

(E) Two redundant *serial data busses*, which allow to connect any navigation equipment with any of the two onboard computers.

Besides the EO-camera all devices of this reference architecture belong to the *standard equipment* of a typical LEO telecommunication and earth-observation mission.

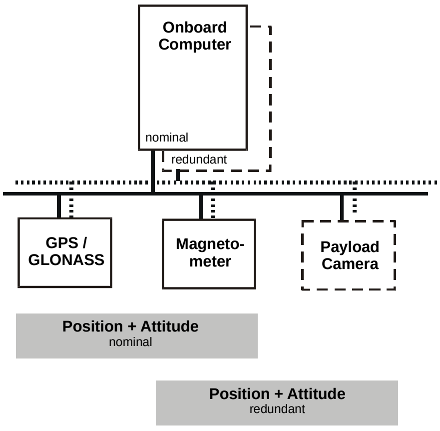


Fig: 1 Reference Hardware Architecture

The availability of an *EO-camera* as payload is obvious for an earth observation mission. But it could be applicable on certain future LEO missions as well, which combine telecommunication and continuous earth observation (EO) monitoring tasks, i.e. traffic monitoring. In these applications as well as in classical EO missions the EO-camera can be used quasi "free of charge" for navigational purposes. This is the reason why it is included in the reference hardware baseline.

3. REFERENCE APPLICATION MISSION

As application reference for performance analyses the *TUD-Satellite "Traffic Eye"* [6] is used. This mission uses a micro-satellite in LEO-orbit (500km, 53° inclination) with a high resolution earth observation camera for road traffic monitoring purposes. The satellite is Earth oriented.

4. NOMINAL GPS/GLONASS OPERATION

In the given section are presented the results of simulation of the specific mode of the mentioned system operation, when for the user position, velocity and attitude determination only a GLONASS/GPS multichannel receiver is used.

The following wide set of uncontrollable factors and errors were considered by the studies: GLONASS&GPS ephemerise definition systematic and random errors due to the errors of the on-ground complex navigation satellites orbit determination; pseudodistance and pseudodistance rate systematic and random errors due to the ionosphere errors, receiver clock drift and internal receiver noise; carrier phase difference measurement systematic and random errors due to the multipath effect, receiver clock drift, internal receiver noise; systematic and random errors of the system initialization due to the errors of the auxiliary sensors data.

During the simulation of the TUD satellite attitude determination process using a GLONASS&GPS receiver the influence of following factors was explored:

various completeness of the GLONASS&GPS navigation satellites constellation; different length of satellite antennae system base; different level of systematic errors.

The following versions of the data processing algorithms has been used: a recursive Bayes algorithm (some modification of Kalman filtering) for user position & velocity determination; a Least Mean Square algorithm for user attitude determination.

All obtained simulation results have been processed using the Monte-Carlo technique.

For the simulation an incomplete GLONASS-system (only 12 satellites) and a complete GPS-system with 24 satellites is assumed

Base, m	Pitch error, deg			Yaw error, deg			Roll error, deg		
	GLO	GPS	GLO+GPS	GLO	GPS	GLO+GPS	GLO	GPS	GLO+GPS
1	0.8	0.575	0.57	0.27	0.37	0.25	0.82	0.58	0.55
2	0.38	0.28	0.28	0.15	0.18	0.14	0.45	0.39	0.27
3	0.25	0.18	0.18	0.1	0.12	0.09	0.29	0.19	0.18

Table 1: Simulation results of attitude r.m.s. estimation error using GPS/GLONASS navigation satellites.

The simulation interval is equal to 86400 sec.

Errors of the TUD satellite position and velocity determination are:

- for GLONASS the r.m.s. error of the TUD satellite position is equal to 25 m; the r.m.s. error of its velocity is equal to 0.5 cm/sec,
- for GPS the r.m.s. error of the TUD satellite position is equal to 100 m; the r.m.s. error of its velocity is equal to 50 cm/sec (taking into account GPS C/A mode of operation).

Errors of the carrier phase differences measurement:

- the r.m.s. error of the systematic error, caused by the multipath phenomenon is varied in the following way: 0.0033m, 0.005m, 0.01m, 0.033m, 0.05m;
- the r.m.s. error of the additive random noise is equal to 0.005m.

The obtained simulation results are presented in the Table 1. This table contains mean values of TUD satellite attitude estimation errors, depending on the simulation input data.

The presented simulation results demonstrate a suitable accuracy of the estimation even by antennae base length about 1-2 meters, especially by utilization both GPS and GLONASS constellations. It is reasonable to emphasize here, that all above presented results are obtained by the maximal values of disturbing factors; so, we can consider this results as guaranteeing ones.

5. BACKUP OPERATION USING MAGNETOMETER

Magnetometer navigation is based on measurements of the geomagnetic field vector by a magnetometer. It is supposed to use magnetometer data as an additional measurement source during acquisition phases or as a backup when the GLONASS/GPS receiver has failed. Autonomous navigation using magnetometers is a problem actively studied worldwide during the last several years [Ref 2]. Magnetometers have proved to be very reliable, small, and cheap devices that provide the capabilities to determine both position and attitude of the spacecraft. Moreover, the autonomous navigation process based on magnetometer has almost absolute stability even with very bad initial estimations: the estimation converges to its stable state even from initial errors of hundreds of kilometers and unknown attitude within some few orbits.

The magnetometer navigation is based on the mathematical description of the geomagnetic field as spherical harmonics.

The filtering approach follows well known Extended Kalman filtering (EKF) techniques which are based on orbit and attitude models of appropriate complexity. For orbit determination the filter uses only the magnitude of geomagnetic field measurements and for attitude estimation the filter uses the full magnetic field vector measurement information.

The main error sources for magnetometer navigation can be grouped in equipment and spacecraft related errors (noise, biases, geometrical offsets, strawfields from other onboard devices) and errors due to the uncertain knowledge of the geomagnetic field. Commonly a frequently updated IGRF model (International Geomagnetic Reference Field) is used, which does not take into account some stochastic disturbances of the magnetic field (e.g. magnetic

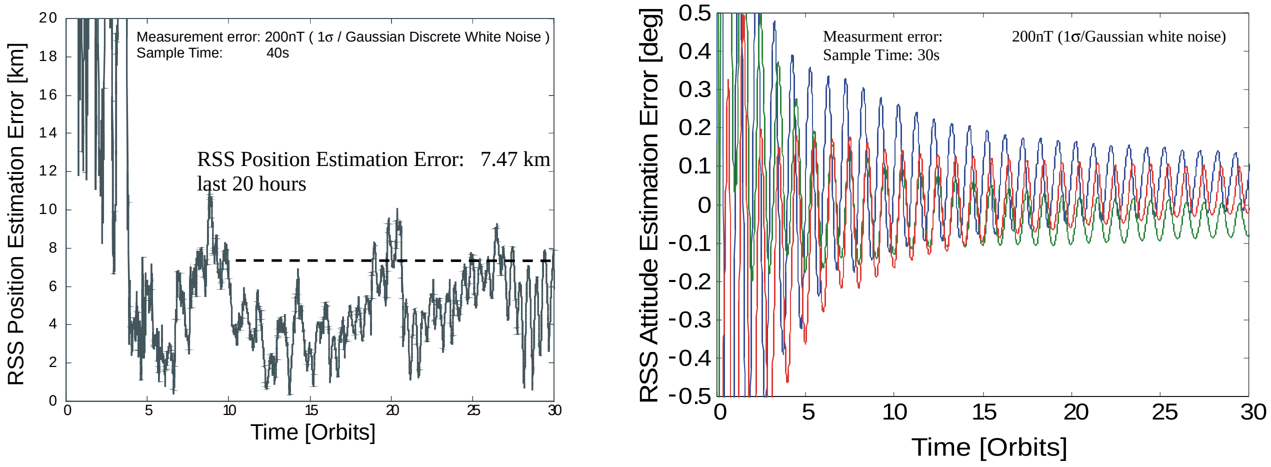


Fig. 2: Position and attitude estimation error of magnetometer navigation

storms). According to flight result analyses the measurement errors are dominated by Gaussian errors and constant systematic errors, which justifies the application of EKF-techniques. The simulation estimation performances results in typical RSS average position errors in the order of 8-10 km and attitude errors in the order of 0.2-0.3 deg (see Figure 2). The evaluation shows clearly the limitations of sole magnetometer navigation in reaching operational performances comparable with the nominal ones.

Additional investigations are performed with real flight data derived from German X-ray satellite ROSAT to verify the obtained navigation results [Ref 1].

6. BACKUP OPERATION USING LANDMARKS

Landmark navigation is based on the comparison of the images obtained by an on-board earth observation (payload) camera and the images of the same areas of the earth's surface stored in the on-board computer.

The simulation has been performed by numerical integration of the differential equations of both orbital and angular motion.

The uncontrollable factors that are present in the considered problem can be divided into three large groups:

1) factors such as type of terrain, cloud cover, illumination conditions, that determine the opportunity to perform measurements, i. e. to perform observations of the areas that contain landmarks,
2) factors that determine the accuracy of observations, i. e. errors of angular observations that result from errors of the image processing, inaccuracy of camera alignment, etc., and
3) the factors that influence the accuracy of the models of motion such as random errors of the initial state vector estimation, the disturbing forces and the torques

The additive error of camera misalignment has been simulated as a combination of two stochastic components: a slowly changing one (simulated by a 1st order shaping filter in each of the three channels) and a rapidly changing one (simulated by a sequence of Gaussian non-correlated random values). As the result, the total error of angular measurements is formed as a combination of the rapidly changing image processing error, individual for each of the landmarks, and of the described camera misalignment error, which is identical for all the three landmarks. The third group of uncontrollable factors is discussed above.

Since there are many uncertainties in the models of the uncontrollable factors, they have been simulated in such a way that their influence is the worst possible, in other words, the simulation results are guaranteeing.

An advanced Kalman-type filtering algorithm described in [Ref 6] has proved to provide adequate results and is applied for the current problem.

For the TUD-satellite reference mission the method provides the solution to the navigational problem with maximum error not worse than 4 - 6 kilometers. The main factors that determine the navigation accuracy (supposing that orbit altitude is fixed) are the camera resolution and field-of view [Ref 4]. The accuracy of the attitude determination is considered in the steady state of the attitude estimation process, i. e. after the transition process has finished.

The results of the study of camera misalignment error with the systematic component on the attitude determination accuracy are given in Fig. 3. Due to almost ideal sensitivity, pitch and roll angle are estimated very well, while yaw is estimated much worse due to much worse sensitivity.

Errors caused by the image processing errors in the pitch and roll channels are not very significant because they are compensated by the perfect sensitivity and redundancy (three objects are used, whereas one is sufficient). In the yaw channel the error is higher due to both worse sensitivity and the image processing error, which is transformed into the yaw determination error almost directly.

The errors of the model of angular motion cause errors in the estimation of the drag force and, hence, of the torque produced by the drag force, which, in their turn, worsen the accuracy of propagation of the attitude and angular rates. The errors of up to 25% in estimation of the magnitude of the disturbing torque raise the error of the attitude estimation by several times. Yaw error is the highest; pitch error is smaller, but still high because the disturbing torque acts in the pitch plane; roll error is the smallest, but still grows with the error of disturbing torque due to cross-link with the yaw channel.

The influence of the camera field of view has been also studied by computer simulation. The results have proved the theoretical supposition: the size of the field-of-view almost does not influence the accuracy of

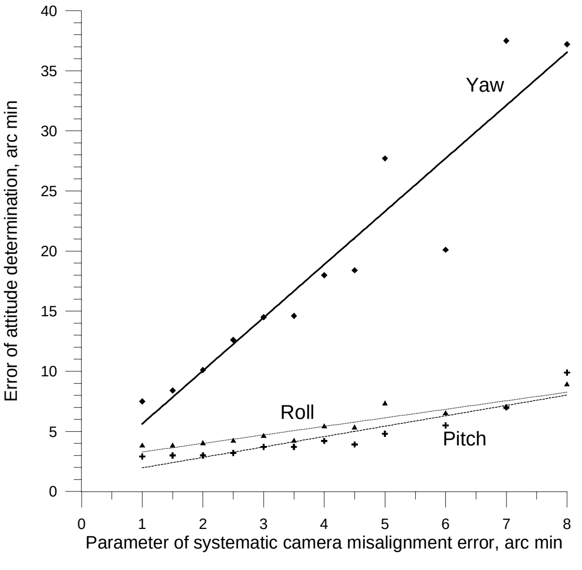


Fig. 3. Influence of systematic camera alignment error on the accuracy of attitude determination.

attitude determination.

The orbit and attitude determination using observation of landmarks on the surface of the Earth is possible with acceptable accuracy: the maximal error of orbit determination for TUD-Satellite does not exceed several kilometers; accuracy of the attitude determination is better than 1 degree. The accuracy significantly depends on the spacecraft orbit, characteristics of the spacecraft and its onboard equipment: orbit determination accuracy grows with altitude, field-of-view and resolution of the camera; attitude determination error significantly increases with camera misalignment error and with error of atmosphere drag torque estimation.

7. DATA FUSION FOR LANDMARK SYSTEMATIC ERROR ESTIMATION

This section contains a brief description of both information fusion technique and results of its simulation. The purpose of the simulation is to demonstrate a possibility to reduce Landmark camera systematic errors, using GPS/GLONASS receiver data.

The following data fusion technique was used:

- Output data of the GPS/GLONASS receiver (accurate estimations of TUD satellite position, velocity and attitude) are used to predict the Landmark camera measurements;
- By comparison of the "predicted" LM^{ref}_{meas} and "true" LM^{real}_{meas} Landmark camera measurements results the refinement of the Landmark camera systematic errors is carried out;
- The obtained value of the Landmark camera systematic error estimation is used later in the Landmark Navigation Algorithm.

Let us point, that the described information fusion technique is simplified one and it is, therefore, most efficient, if one considers Landmark camera systematic errors as time invariable ones. In the general case, if the Landmark camera systematic errors are considered as Gauss-Markov models (i.e. so called shaping filters) it is necessary to accumulate the current information about the systematic error estimation. Meanwhile, the simplified information fusion technique was used by the simulation even in the case, if the Landmark camera systematic errors were considered as a time variable ones to obtain guaranteeing results.

The input data by the simulation were accepted the same like by both Nominal and Backup Modes of the Operation simulation. The first order shaping filter was used to represent the Landmark camera systematic errors:

where

c is a vector of the Landmark camera systematic errors,

A,B are a diagonal matrices of the corresponding dimensions,

ξ is a vector of the standard white noises.

The simulation results are presented in the Figures 4. Figure 4-1 demonstrates TUD satellite attitude estimation errors, if only the Landmark camera is used and the systematic errors are absent at all. Figure 4-2 shows the same results if the Landmark camera systematic errors are not observable. Figure 4-3 shows the attitude estimation errors if the information fusion is carried out. Figure 4-4 shows the influence of the so called "correlation interval" of Landmark camera systematic error on the accuracy of the TUD satellite attitude estimation.

The analysis of the obtained results let us liberty to say, that the information fusion technique allows significant to reduce the influence of the Landmark camera systematic errors on the satellite attitude estimation accuracy in the worst case.

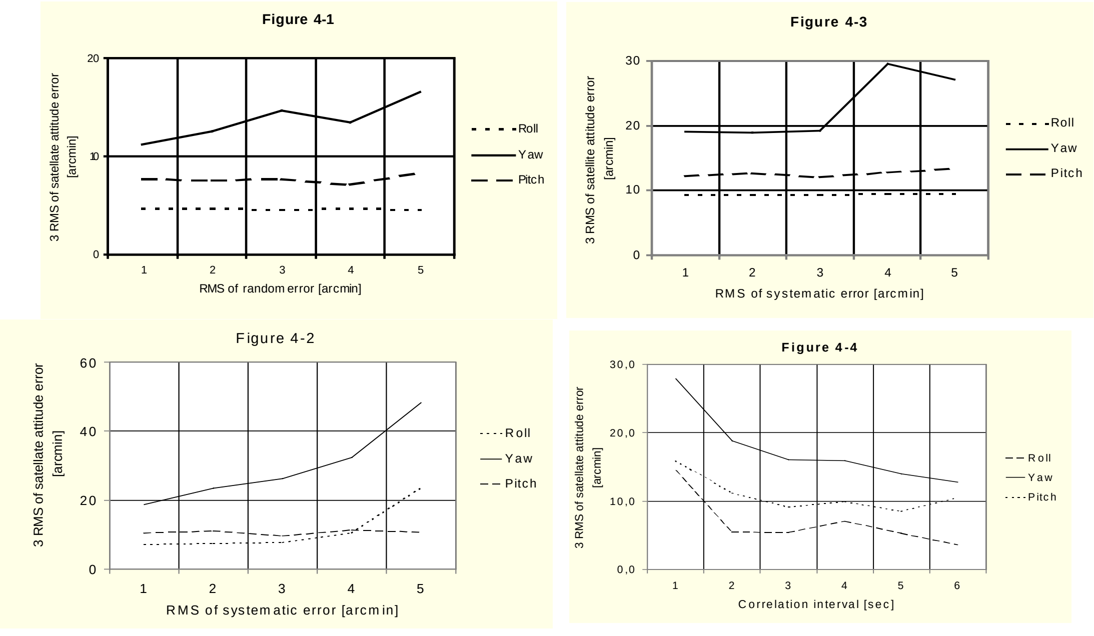
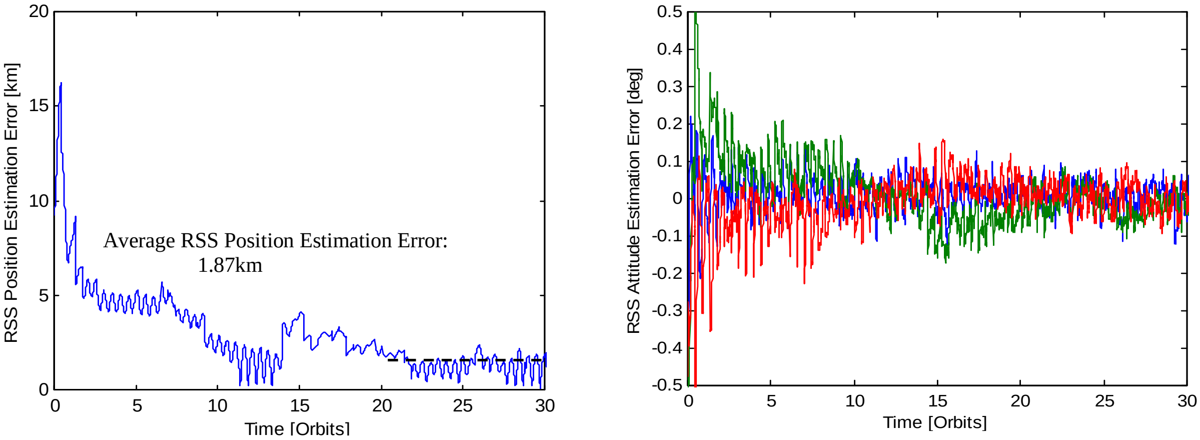


Fig. 4: Simulation results of information fusion



Simulation Parameters:		
	Magnetometer Measurement Error:	200nT (Gaussian white noise)
	FOV / Swath Width:	52deg / 500km
	Number of LM-Measurements per Orbit:	2
	Errors:	25 arcmin (Matching error)

Fig. 5: Position and attitude estimation error of combined magnetometer and landmark navigation

8. DATA FUSION FOR COMBINED MAGNETOMETER AND LANDMARK NAVIGATION

The study of accessible estimation performances based on the sole use of one backup sensor alone (magnetometer, landmark) shows clearly the limitations of single information sources. Magnetometer based information suffers from measurement errors resulting mainly from geomagnetic field uncertainties. Landmark based information suffers from rare updates due to road availability and disturbing weather conditions (clouds) as well as from the poor initialisation robustness as outlined in the previous section.

A typical performance result using a *centralised filter* [Ref 3] based on *fusion* of magnetometer and landmark measurement data is shown in Figure 5. The simulation shows quite well the benefit of using complementary sensor data.

9. SUMMARY

This paper describes an autonomous navigation concept for LEO satellites based on the synergetic maximum use of onboard equipment. The combination of dedicated navigational equipment (magnetometer), payload equipment (earth observation camera) and subsequent *information fusion* algorithms allows to build up minimum hardware systems with functional redundancy capabilities. The concept is evaluated for the TUD-Satellite road traffic monitoring mission *Traffic Eye* as application reference. The presented results for position and attitude estimation and the proposed information fusion techniques show the capabilities of such a navigation system and allow some first estimations on reachable performances.

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