EUROSIM '95
F. Breitenecker and I. Husinsky (Editors)

Modeling and simulation of Navigation Systems: An INS simulation Matlab toolbox

J.A.López Orozco [a] , P. Ruipérez [b] , J.M. de la Cruz [a] , J. Aranda [b]

[a] Dpto. de Informática y Automática. Facultad de Ciencias Físicas. Universidad Complutense de Madrid. Ciudad Universitaria, 28040 Madrid, Spain.

[b] Dpto. de Informática y Automática. Facultad de Ciencias. Universidad Nacional de Educación a Distancia. C/ Senda del Rey, s/n, 28040 Madrid, Spain.

This paper introduces a Matlab toolbox for design, analysis and simulation of Inertial Navigation Systems (INS) and its integration with systems of external aid, especially GPS. Our functions can be utilised individually or combined with other functions created by the user in order to test other INS algorithms, filters, etc. This toolbox includes functions to simulate inertial sensors, GPS measurements, Kalman filters, navigation systems, ...

1. INTRODUCTION

The main purpose of an Inertial Navigation System (INS) is determine the position, velocity, attitude and heading of the vehicle. The three basic functions of an INS are sensing, computing and outputting. The accelerometers and gyros perform the sensing function and send their measurements of acceleration and angle rate to the computer. The computer uses these data to calculate velocity, position, and attitude and generates appropriate signals for the control system and the display unit [1-2].

The INS performance is primarily limited by its sensors error source, such as gyro drifts and accelerometer errors. These sources cause errors in the computed position and velocity, which increase with time. The obtained positions and velocities are excellent over short time periods. Typically, the position information of an INS degrades at a rate of 1,500 meters/hr. So it is advisable supplement this system with other external devices. In these cases, we get very high precision. When INS measurements are integrated with other measurements of external navigation devices, the INS is an aided INS. The external navigation devices can be position aids, velocity aids or attitude aids. Examples of position aiding devices [3], are GPS (Global Positioning System), TERCOM (Terrain Contour Matching), LORAN (Long-Range Navigation) and TACAN (Tactical Air Navigation). Doppler radar and GPS can both provide velocity updates. Baro-altimeters are utilized for altitude aiding.

Among the positioning and navigation aiding systems, it is perhaps GPS coupled with newer and better-designed field-qualified receivers that provide unprecedented positioning and navigation capability. The GPS contribution to navigational accuracy has been clearly established for both military and civil applications. The GPS measurements, properly combined with information from the INS and other kind of sensors, provides exceptionally high accuracy position, velocity, and time.

The toolbox has tools for analysis, modeling, simulation and test of INS external aid integration. The choice of the integration architecture can affect performance, integration cost, maintenance cost and many other capacities of the system (see some examples in [4-6]). The toolbox implements some GPS/INS integration techniques. The integration is evaluated by off-line simulation.

The toolbox has been built using Matlab, so that all the advantages of the Matlab's programming environment can be used. It allows the users to create their own applications and make use of graphics and others characteristics of Matlab functions.

This paper shows the use of the toolbox in the INS/GPS integration. The rest of this paper is divided in four sections: section 2 enumerates different available toolbox functions; section 3 presents a real example of INS/GPS integration in a terrestrial vehicle and shows the possibilities of this tool; section 4 presents the conclusions of the paper.

2. TOOLBOX FUNCTIONS

All the functions of this toolbox have been created to simulate Inertial Navigation Systems with or without aid. However, they could be utilized individually or combined with other new ones in order to test other integration algorithms, filters, etc. The functions are classified in five groups (Table 1):

Simulation functions: this group includes functions to: generate paths, introduce the sensor models (bias, noises, misalignment errors, ...), and simulate gyros, accelerometers and GPS measurements. A/C code GPS receiver and DOP (Dilution Of Precision) simulators compute satellite orbits and select those satellites with the best geometry among all availables in order to give good positions.

Mathematical functions: integration functions, transformation between different coordinate systems (e.g. earth-centred, inertial, topocentric,...), quaternion computations, transformations between quaternions and Euler angles, etc.

Navigation functions: these functions compute Coriolis accelerations, gravitational accelerations or terrestrial angular rate. Here, the own navigation functions are included to simulate the vehicle and integrate the whole INS system. These functions allow to reset periodically the navigation system.

Analysis and design functions: Analysis, design and tuning of Kalman filters, and inertial sensors modeling. Similar functions are met in [7].

Monitoring functions: functions to display simulation results. They allow to display the INS measurements, satellite positions, sensor measurements and simulation results.

3. USING THE TOOLBOX

The best way to describe the toolbox possibilities is by showing through an example how this tool is used. Therefore, we will make a step-by-step GPS/INS integration with several Kalman filter implementations. The session outline can be seen in Table 2.

- Use a path generator in order to elaborate the hypothetical path that we wish the vehicle carry out. The user can choose between a stopped vehicle simulation or a moving vehicle simulation. In the latter case, the user selects two geographic positions and a predetermined

Table 1
Some toolbox functions

Function	Description
	Path generators and sensor simulators
gen	Minimal path between two positions
gendef	Compute a determined path between two positions
simacel	accelerometers simulation
simgyro	Gyros simulation
gpspos	GPS position and attitude measurements simulation
gpsrang	GPS pseudoranges simulation
simalt	Altimeter simulation
setacel	Accelerometer model
setgyro	Gyros model
setgps	GPS model
setalt	Altimeter model
	Mathematical functions
cua2eul	Compute Euler angles from Quaternion
eul2cua	Compute Quaternion from Euler angles
matorto	Cbn matrix orthonormalitation
intcbn	Cbn matrix integration
	Navigation functions
navcbn	Strapdown navigation with Cbn matrix integration
navqua	Strapdown navigation with quaternion integration
gravity	Earth's gravitational acceleration
coriolis	Coriolis acceleration
	Analysis and design functions
anacov	Covariance analysis
insff	Feedforward indirect Kalman filter
insfb	Feedback indirect Kalman filter
mocafil	Monte Carlo analysis
	Monitoring functions
gpsplot	GPS satellites plots
navplot	Navigation positions plots
errplot	Navigation errors plots

path: fixed path (circle, along meridians and parallels, ...) or minimal path. In this example is assumed our vehicle travels along meridians and parallels.

- Inertial sensor models. At this time, we select the bias, misalignment, and others errors of gyros and accelerometers. Also, we choose ionosphere corrections and other GPS features.

- Navigation algorithm and INS simulation according to the designated path and the sensor outputs. The navigation type used is Strapdown and there are two possibilities: integration of the Cbn matrix (transformation matrix relating the body coordinate frame to the geographic coordinate frame) [1], and quaternion integration [8].

Table 2
Outline of a simulation session

```
% Simulation of a path followed by the vehicle
        [Pos, Vel, Wb, Ab, t]=gen_def(Pos0, PosE, Vel0, T, Tray);
% Inertial sensors models
        Ac=setacel('bias', [bax,bay,baz]);
        Ac=setacel('misalign', [mxx, mxy, mxz, ...]);
        Gy=setgyro('bias', [bgx,bgy,bgz]);
        Gy=setgyro('noise', Param,type);  % ... until finish the whole model
% Sensor simulations
        Abac=simacel(Wb, Ab, Ac);
        Wbgy=simgyro(Wb, Ab, Gy);
% Navigation algorithm and INS simulation
        [PosN,VelN,euler]=navcbn(Wbgy, Abac, Pos0, Vel0, euler0, T, t, ParamN);
% Analysis and design of low-order Kalman filter
        load mdinsgps;
        rank(obsv(A,C))
        anacov(A,B,C,Q,R, Am,Bm,Cm,Qm,Rm,'covtemp.mat');
% GPS simulation and error models
        Gp=setgps('troposf', Errt);
        [Wks, Cel, dist]=satel(PosOb, t);
        [PosG,VelG,track]=gpspos(Wks, Cel, dist, Gp);
        dispgps(Wks, Cel, dist, Nsat, 'map');
% INS/GPS simulation by Indirect Feedback filter
        [PosE, VelE, P]=insfb(PosN, VelN, PosG, VelG, T, Ac, Gy, Gp, reset);
```

- Kalman filter design. The analysis and design of low-order Kalman filters requires several steps:

a.- INS and GPS model. The matrices that define the model must have been calculated by the user.

b.- Observability analysis.

c.- Covariance analysis and error budget table. The result is saved to a file.

d.- Low-order filters are obtained from the covariance analysis.

e.- Analysis of the proposed filter under parameter uncertainties.

- INS/GPS simulation
  - a.- Definition of GPS error model.
  - b.- Display of the visible satellites at a given period of time. Figure 1 shows four simulated satellites.
  - c.- Integration and simulation of INS/GPS.

There are two very important aspects of implementation of Kalman filter in conjunction with inertial systems: total state space versus error state space formulation (also denoted direct versus indirect filtering), and feedforward versus feedback mecanizations [9].

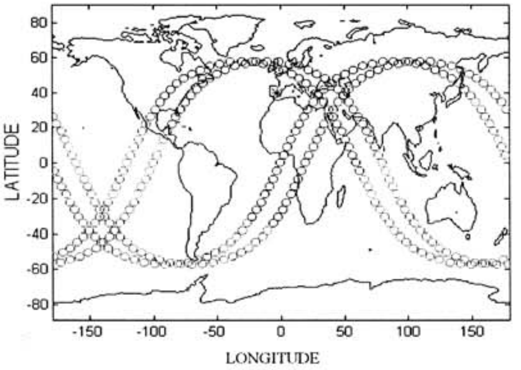

Figure 1. Tracked GPS satellites.

Total state space Kalman filters are in the INS loop and they are not implemented because they have several drawback: The filter would need a very fast sample rate and would have to perform all computations within this short sample period. The Kalman filter need an adequated linear system model, and such a total space model does not exist. If the filter failed, the entire navigation system would fail.

We are implementing indirect Kalman filters, which estimate the errors in the navigation and the attitude information using the difference between INS and external data. In this case, the filter is based in a set of inertial system error propagation equations, which are relatively well developed, low frequency, and very adequately represented as linear. Besides, the filter is out of the INS loop. Thus, the indirect Kalman filter order and sample rate can be much lower than that of a direct filter.

We have done two types of indirect Kalman filter implementations: feedforward an feedback. Following the feedback scheme, the Kalman filter provides periodically and estimating of the INS errors, which are used to update the INS. Figure 2 displays an example of the East position error when the whole system is updated every 100 seconds .

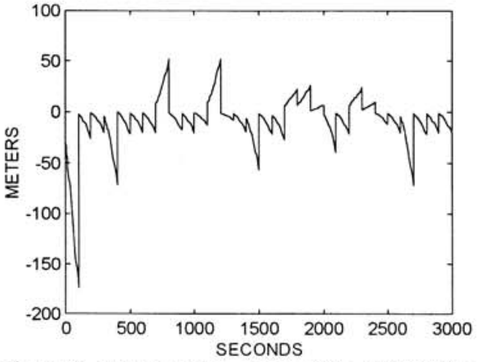

Figure 2. East position error of the INS/GPS system.

4. CONCLUSIONS

We have created a Matlab toolbox for analysis, design and simulation of INS with and without aid. Its use has been showed with an INS aided by GPS. Suboptimal and cascade filters can also be designed and analysed.

Different navigation algorithms can be build using our toolbox functions. Besides, a lot of these functions can be used as a standalone program, e. g. covariance analysis functions and observability of Kalman filters can be useful tools for designing and analysing Kalman filters.

The toolbox functions will be got soon through Internet.

Acknowledgement: This work has been partially supported by the Spanish CICYT project TAP94-0832-C02-01.

REFERENCES

1. K. R. Britting. Sc. D. Inertial Navigation System Analysis. *Wiley-Interscience, a Division of John Wiley & Sons, Inc. New York 1971.*
2. B. Stieler. Gyroscopic Instruments and their Application to Flight Testing. *AGARD Flight Test Instrumentation Series. AGARDograph nº 160, 1982.*
3. M. Kayton. Navigation. Land, Sea, Air, and Space. IEEE Aerospace and Electronic Systems Society, 1990.
4. Grep Hyslop, Dennis Gerth and John Kraemer. GPS/INS Integration on the Standoff Land Missile (SLAM). *IEEE AES magazine, pp. 29-34, July 1990.*
5. Alfred Kleusberg. Integration of INS and GPS Measurements. *High Precision Navigation. Ed Springer-Verlag, pp. 136-146.*
6. Dan Simon and Hossny El-Sherief. Real-Time Navigation Using Global Positioning System. *IEEE AES magazine, pp. 31-37, January 1995.*
7. J. Aranda, J. M. de la Cruz, P. Ruiperez and S. Dormido. Software for Modeling, Simulation and Design of Navigation Systems. *Math Modelling and Sci. Computing. Vol. 2, pp. 222-227, 1993.*
8. Paul G. Savage. Ph. Advances in Strapdown Sensors. *AGARD Lecture Series nº 133, pp. 3-1; 3-30.*
9. P. S. Maybeck. Stochastic models, estimation and control. Vol. 1. New York: Academic Press, 1979.

Eurosim'95
Simulation Congress

Proceedings of the 1995 EUROSIM Conference, EUROSIM '95,
Vienna, Austria, 11-15 September 1995

Edited by

Felix Breitenecker
Irmgard Husinsky
Technical University Vienna
Vienna , Austria

N-H

1995
ELSEVIER
Amsterdam • Lausanne • New York • Oxford • Shannon • Tokyo

ELSEVIER SCIENCE PUBLISHERS B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

ISBN: 0 444 82241 0

This book is printed on acid-free paper.

Printed in The Netherlands.