Extended Kalman Filter Based INS/GNSS Integration For Launch Vehicle Navigation

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Extended Abstract

Abstract

Navigation is a critical technology for achieving the mission success and accuracy of a Launch vehicle. ISRO's Launch vehicles mainly use an Inertial Navigation System (INS) for this purpose in the closed loop NGC (Navigation, Guidance & Control) system. For the ongoing short duration missions the navigation accuracy obtained with Inertial Navigation System in pure inertial alone mode is good enough for precise injection of satellites to orbit. All inertial navigation systems suffer from integration of sensor drift which results in large errors over time. For ISRO's advanced missions like long duration missions, reentry vehicles, Reusable Launch Vehicle (RLV) and manned missions, high reliability and accuracy in various mission phases cannot be ensured using INS alone. An integrated navigation system consisting of multiple navigation systems like INS, GNSS etc is used for such missions. The end to end design aspects, development and validation of the Extended Kalman Filter for integrating INS, GNSS and the flight performance of the Hybrid Navigation System achieved are presented in this paper.

In Space Capsule Recovery Experiment (SRE), which is the first Indian re-entry mission, excellent navigation accuracy has been achieved using a 12 state scheduled Gain EKF in the orbit transfer and final de-boost phase. For advanced missions like RLV, landing phase requires very high navigation accuracy. To meet the stringent accuracy requirements, a precise hybrid navigation system based on INS, GNSS and Radar Altimeter (RA) is used in closed loop. A robust 15 state EKF for integration of INS, GNSS data is designed and developed to achieve the mission.

For a typical Polar/GTO mission, a real-time Extended Kalman Filter is used in 'open loop feed forward' configuration for fusion of data from strap-down Inertial Navigation System and GNSS. The design of the real-time EKF involves development of various novel techniques like real-time gain computation, measurements based filter initialization scheme for fast convergence etc. Several error handling schemes for robustness are also designed, developed and validated.

1. Introduction

An efficient algorithm for fusion of data from various systems like INS, GNSS and solutions for an accurate and robust state estimation are considered a key technology to be developed for future missions. As a first step in achieving this goal, a GPS Aided Inertial Navigation System (GAINS) was developed and demonstrated successfully as part of Advanced Avionics Module on PSLV-C8 flight. The navigation accuracy is achieved in GAINS by using a real time EKF in feed forward configuration for data fusion of INS and GNSS, and it is currently used in ISRO's Polar/GTO missions for Real time monitoring of orbital parameters and Preliminary Orbit Determination.

2. System Configuration

The configuration of GAINS system used in PSLV/GSLV missions is given in fig1.The GAINS will have a separate 1553B bus (GAINS bus) for interfacing with the GPS receiver. The GAINS processor (GAINSP) acquires the GPS data through the GAINS bus. The GAINS processor collects the data from the INS from the broadcast message of the prime and redundant NGCP.

The Extended Kalman filter resident in the onboard GAINS processor estimates the INS position and velocity errors. The aided navigation outputs are generated by using the estimated INS errors and are used to compute the orbit parameters & monitoring parameters.

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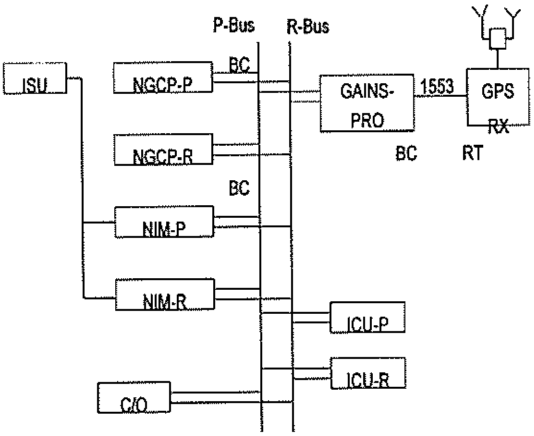
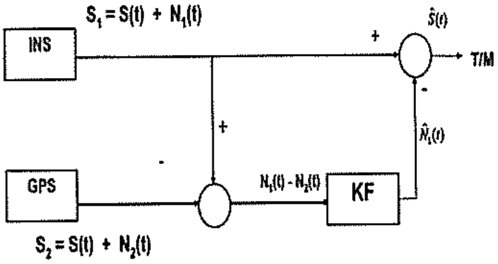


Fig 1: GAINS Configuration

3. System Dynamics and EKF Architecture

An open loop feed forward configuration (Fig 2) of EKF is used in Launch vehicle applications. The filter estimates the INS error (position and velocity error) and corrects in the forward path.



$N_2(t)$: position and velocity error of GPS
$N_1(t)$: position and velocity error of INS

Fig 2: EKF Architecture

The model for the Kalman filter is the error dynamics of the INS. The input measurement to the Kalman filter is the difference (INS-GPS). The state variables of the filter are selected after considering the mission trajectory and velocity, position accuracy requirements so that the accuracy is met.

INS Error Dynamics Model

The EKF used in GAINS system uses 15 state variables

$$X = [\Delta x\, \Delta y\, \Delta z\, \Delta vx\, \Delta vy\, \Delta vz \quad bx\, by\, bz \quad mx\, my\, mz \quad dx\, dy\, dz]^T$$
$$= [\text{pos err, vel err, acc bias, ref frame misalignme nt, gyro drift}]^T$$

X: Error state of INS

The error model can be represented as:

$$\dot{X} = AX + w,$$
Cov (w) = Q, w: white Gaussian noise

$$A_{15x15} = \begin{bmatrix} 0_3 & I_3 & 0_3 & 0_3 & 0_3 \\ J_G & 0_3 & C_b^I & Acc & 0_3 \\ 0_3 & 0_3 & 0_3 & 0_3 & 0_3 \\ 0_3 & 0_3 & 0_3 & 0_3 & CCM \\ 0_3 & 0_3 & 0_3 & 0_3 & 0_3 \end{bmatrix}$$

CCM: 3x3 sub matrix whose elements are obtained from C_b^I matrix.

Discrete Model for Kalman Filter

The discrete form of the model can be represented as :

$X_{k+1} = \phi_k X_k + w$

Cov(w) = Q, w: white Gaussian noise

$X_0 = X(0)$, Cov $X_0 = P_0$

Measurement Equation

The difference between INS & GPS in position & velocity is the measurement for the filter. The first 6 states are directly measured.

$Z_k = HX_k + e$, $Cov(e) = R$

$$H_{6x15} = [I_{6x6} \quad O_{6x9}]$$

3.1 Filter Implementation

The standard Kalman filter implementation with sequential measurement update is implemented.

1) Time Update

(i)compute state transition matrix ϕ_K

$$\phi_K = I + A_K\, dt + (A_K\, dt)^2/2$$

(ii)Predict state & covariance , one step

$$X_{K+1} = \phi_K X_K ,$$
$$P_{K+1} = \phi_K \; P_K \phi_K^T + Q$$

2) Measurement Update

(i) Form Measurements,Z=INS-GPS

(ii) Predict measurement & compute innovation

$$\hat{Z} = HX_{K+1}, innovation = Z - \hat{Z}$$

Sequentially process the measurement one at a time and do steps (iii) and (iv) for all six measurements.

(iii) Compute kalman gain

$$K_i = PH_i^T [H_i P H_i^T + R]^{-1}$$

(iv) Update state (correction) & covariance:

$$X_{K+1} = X_{K+1} + K_i[Z_i - \hat{Z}_i], \qquad P = [I - K_i H_i]P$$

H_i is the ith row of measurement matrix

The flow chart of the Kalman Filter implemented in GAINS system is shown in Fig 3.

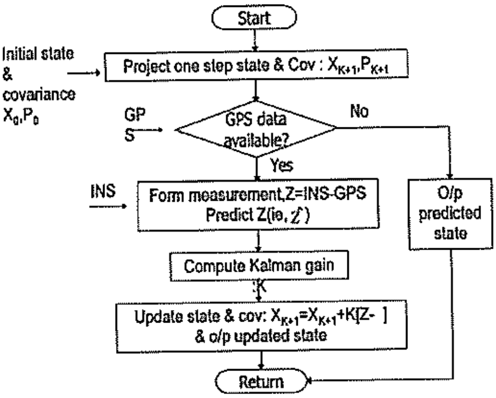


Fig 3: Flow chart of EKF Implementation

4. Model Validation and Process Noise Estimation

INS error dynamics model for the chosen 15 states was analytically derived. The 15 state discrete time INS error dynamics model is validated by simulation. A complete INS truth model is used as reference. The EKF states are propagated using the state transition model and is compared with the true states from the truth model.

The process noise Q is estimated by an 'Monte Carlo' simulation by comparing the complete INS model and the state transition model. All the INS error parameters are perturbed in a Monte Carlo sense and the error per step in the state transition model of the EKF is obtained for the entire trajectory. The process noise is obtained by computing the ensemble statistics of the error per step of the model.

The Q is computed from 100 runs where all the modeled and unmodeled errors of the INS are perturbed. The selected Q is validated by 1500 Monte Carlo runs including off nominal mission scenarios.

5. Filter Robustness

Robustness of the Extended Kalman Filter used in GAINS system is ensured by providing various levels of integrity checks and implementing logics for handling Kalman filter start, Latency correction etc.

The GNSS data validity checks are done at input level before stat of the Kalman filter. The data is validated by ensuring:

- GNSS integrity/checksum check
- GNSS receiver (hardware) check
- Time synch validity check
- Availability of fresh solution
- Availability of solution in 3D mode
- GNSS PDOP checks (PDOP < 10)

The following logics are also implemented in the EKF for ensuring robustness:

- GNSS data loss handling
- Rejection of GNSS wild sample [(measured - predicted) > limit]
- Stop aiding on persistence of any error (50s)
- KF prediction mode under data loss after KF convergence
- INS data correction starts only after (100sec) initial convergence.
- Start of KF only when GNSS data is available (5 samples continuous)
- Restart of KF if normalcy occurs after continuous data loss
- Restart of KF if normalcy occurs after continuous residual error
- Restart of KF if normalcy occurs after continuous KF diagonal covariance error.

6. Design Validation

The design of the EKF for Launch vehicle applications is validated under the following conditions:

1. Low and High measurement noise
2. GNSS data loss (continuous & intermittent)
3. GNSS wild samples: multiple burst of noise
4. GNSS latency: data synchronization
5. Actual GNSS error obtained from RF simulation of Flight receiver
6. Perturbation cases
    - Up to $\pm 3\sigma$ INS & GNSS errors
    - GNSS data loss
    - GNSS data with wild samples
    - Q perturbation

7. Results

The GAINS system is being successfully used in ISRO's Polar/GTO missions. The statistics of performance of the system for the missions is given in the table below:

Table 1: GAINS performance for Polar missions

Mission Id	GAINS Accuracy		
	Apogee (km)	Perigee (km)	Inclination (deg)
PSLV C20	0.9	0.1	-0.001
PSLV C19	0.4	0.2	0.003
PSLV C18	-0.1	0.9	0.002
PSLV C15	0.3	0.1	0.001
PSLV C14	-0.1	0.02	-0.003
PSLV C12	0.02	-0.9	0.0007

Table 2: GAINS performance for GTO missions

Mission Id	GAINS - POD		
	Apogee (km)	Perigee (km)	Inclination (deg)
PSLV C17	4.3	0.5	-0.001

The results given in the table indicate that the performance achieved by GAINS in Polar/GTO missions is of the order 0.3 m/s velocity error over all.

A typical example of Position and velocity errors estimated by GAINS is shown in fig 4 below. A comparison of aided and INS state vectors are shown in Fig 5.

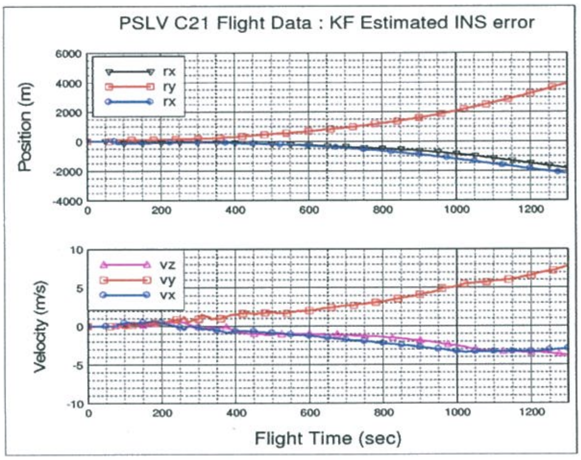


Fig 4: KF Estimated INS errors

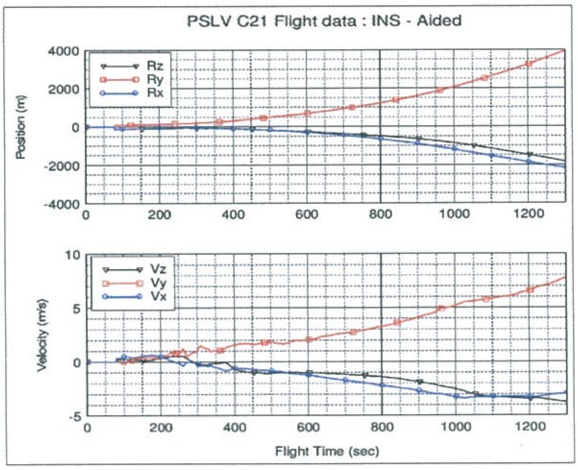


Fig 5: Comparison of INS and Aided state vectors

For SRE, a scheduled Gain EKF is used, where Kalman Gain is stored and scheduled based on events. The aided position,velocity errors obtained in SRE is given in Fig 6.

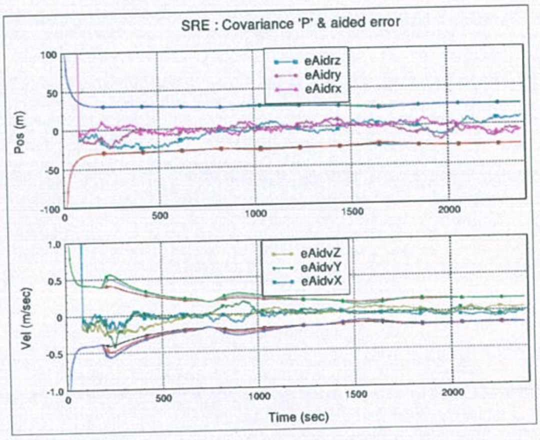


Fig 6: Aided Position, velocity Errors

8. Conclusion

A robust Extended Kalman Filter is designed for integrating INS and GPS data for use in Launch vehicle navigation. The design of the filter is extensively validated through simulation studies and proven successful in PSLV/GSLV missions. The system configuration, system dynamics model and the EKF architecture is presented in this paper. The model validation techniques, design validation are also explained. The performance of the system in PSLV/GSLV/SRE missions is also given. The EKF is successfully used in ongoing missions for preliminary orbit determination and ready for integration in reentry missions like RLV.