GPS/INS/RA data fusion for precise altitude estimation in re-entry and landing missions

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Abstract—In a re-entry & landing mission, to initiate the landing manoeuvres well before touchdown, precise knowledge of altitude is a must. This makes altitude a critical parameter for vehicle guidance in a landing mission. For high accuracy applications, Radar Altimeter (RA) is the candidate. It gives submeter level accuracy for lower altitude range, but its accuracy deteriorates as altitude goes up. RA being an RF system, there could be discontinuity or interruptions in the output. INS ensures continuous availability of the measurement, but suffers from low accuracy. Medium level accuracy can be achieved using the GPS aided INS (GAINS) system. To overcome the drawbacks of standalone systems, an efficient data fusion technique making use of altitude's from INS, GPS and RA is proposed. The fusion algorithm, the simulation results under various scenarios are presented in this paper.

Keywords—INS, GPS, RA, GAINS, KF, Data Fusion, Observer

I. INTRODUCTION

Inertial Navigation System (INS) is a stand-alone system based on inertial sensor measurements for generating the navigation parameters of a vehicle without any discontinuity. Stand-alone INS cannot meet the altitude accuracy requirements of a re-entry & landing mission, as INS errors grows with time. In order to improve the accuracy of the INS outputs, GPS aiding is used. The GPS Aided INS (GAINS) estimates the errors in INS position, velocity which is used to correct the navigation outputs in a feed forward sense. The aided position is used for determining the altitude of the vehicle using an oblate earth model. This aided altitude will have a medium level accuracy, which is not sufficient in the final landing phase. Radar Altimeter (RA) makes use of RF ranging technique for determining the geographic altitude of the vehicle. RA being a RF system, it has the drawbacks of (1) low accuracy for high altitude range, (2) discontinuity or interruptions in the output.

An efficient technique is proposed to overcome the drawbacks of standalone systems. At higher altitudes, aided altitude is used for closed loop guidance. Further, when RA becomes operational the altitude is estimated by fusion of RA and aided altitude. This is achieved by observer based estimation of error in aided altitude using the altitude information from RA. The estimated error is used to correct the aided altitude for use in closed loop guidance. The overall configuration of the closed loop NGC is given in fig-1a.

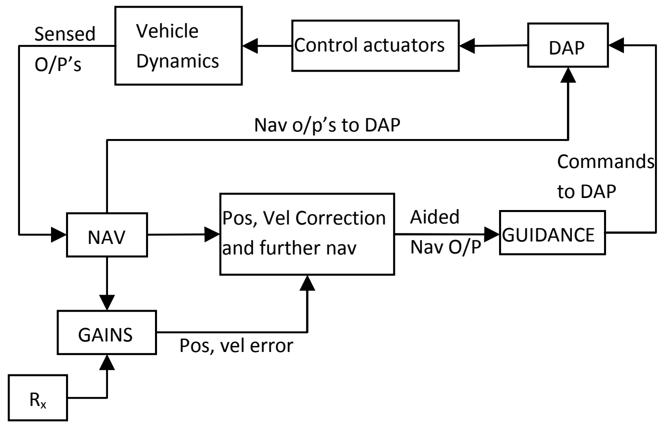

Fig 1a: Configuration of closed loop NGC with GAINS in closed loop

II.GPS AIDED INS SCHEME

A 15-state Kalman Filter is used to estimate the error in INS position and velocity, using the GPS measurements (Fig 2a). The INS state vectors are updated using the estimated errors to generate aided position and velocity. An oblate earth model is used to estimate the altitude of the vehicle from the aided position vector. The aided altitude is used by the Closed Loop Guidance (CLG) until RA becomes operational. Once RA becomes operational, the direct altitude measurement from RA may be used by CLG. This

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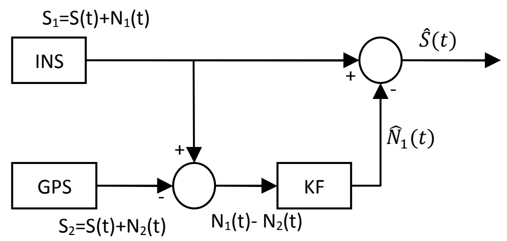
sudden switching from aided altitude to RA altitude will result in a sudden transient in the altitude going to CLG which is not tolerable. Intermittent failures in RA may also lead to transients in altitude. To avoid this, a data fusion technique is proposed for altitude estimation from RA and aided altitude.



N_2: position and velocity error of GPS
N_1: position and velocity error of INS

Fig 2a: Block schematic of GPS aided INS position & velocity computations

III. DATA FUSION TECHNIQUES: TRADE-OFF

A simple and computationally efficient method of fusion is to take the weighted average of the RA and aided altitude. This technique involves scheduling of the weightages for RA altitude and aided altitude. To ensure smooth transition in altitude going to CLG, the weightage for RA altitude is slowly increased from initial low value to a final value of 1. The main disadvantage of this method is it does not have any past history. So in case of a intermittent failure in RA, aided altitude is used which gives sudden transient in altitude going to CLG. So filter based approach is chosen for altitude data fusion.

The error in the aided altitude is taken as the state of the filter. The filter state is assumed as constant within the computational step size, taking into account the slow varying nature of INS errors. The difference in aided & RA altitude is taken as the measurement. The state equations with altitude error as state and difference in aided and RA altitude as measurement are

$$X_{k+1} = X_k \quad \ldots (1)$$

$$Z_k = X_k \quad \ldots (2)$$

Where X_k : current state, Z_k : measurement

In filter based approach, Kalman filter is a very efficient technique for data fusion. In Kalman filter based fusion the final filter gain will settle to a low value i.e. the measurements will be given a low weigthage. Since RA gives a measure of the geographic altitude of the vehicle, it should be given more weightage. This is to capture the altitude changes due to terrain variations. So Kalman filter based fusion of altitude is not suitable for this particular application.

It is proposed to use observer based fusion technique for estimating the altitude from RA and aided altitude. The block diagram for the observer is given in figure 3a.

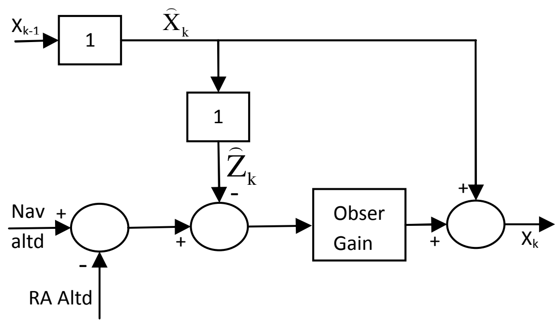


Fig 3a: Block Diagram of the Observer

The initial state of the observer is taken as zero. The observer state is propagated using the equations given below

Propagation:

$$\hat{X}_k = X_{k-1} \quad \ldots\ldots\ldots\ldots (3a)$$

$$\hat{Z}_k = \hat{X}_k \quad \ldots\ldots\ldots\ldots (3b)$$

Measurement:

$$Z_k = Nav_{altd} - RA_{altd} \quad \ldots\ldots\ldots\ldots (4)$$

Correction:

$$X_k = \hat{X}_k + G(Z_k - \hat{Z}_k) \quad \ldots\ldots\ldots\ldots (5)$$

Where

$\hat{X}_k$: is the predicted state
$\hat{Z}_k$: is the predicted measurement
Z_k: actual measurement
X_k: estimated state (error in aided altitude)
G: gain of the observer

This estimated error state is used to correct the aided altitude. The gain of the observer is suitably designed so as to meet the guidance requirements. The scheduling of the observer gains is done based on the convergence of the observer state. The initial observer gain is designed such that there is a smooth transition in the altitude given to guidance. Once the observer state reaches a steady state value a higher gain is used in order to give more weightage for RA altitude.

IV. RESULTS AND CONCLUSIONS

The results obtained using the above proposed scheme is presented in figures 4a-4d. The results show the comparison of the error in altitude obtained from three different schemes. Scheme-1 shows the error in altitude obtained by the proposed technique, scheme-2 shows the error in aided altitude and scheme-3 shows the error in altitude obtained by switching between RA altitude and aided altitude based on the availability of data from RA. The results show the altitude error behaviour for different test cases.

A simple and computationally efficient method is proposed for altitude fusion of INS/GPS/RA. This method eliminates all the drawbacks of individual standalone systems used for altitude measurement. The results show, the proposed scheme gives an accuracy of less than 1m in all the test scenarios.

Figure4a: Nominal case(INS, GPS and RA normal)

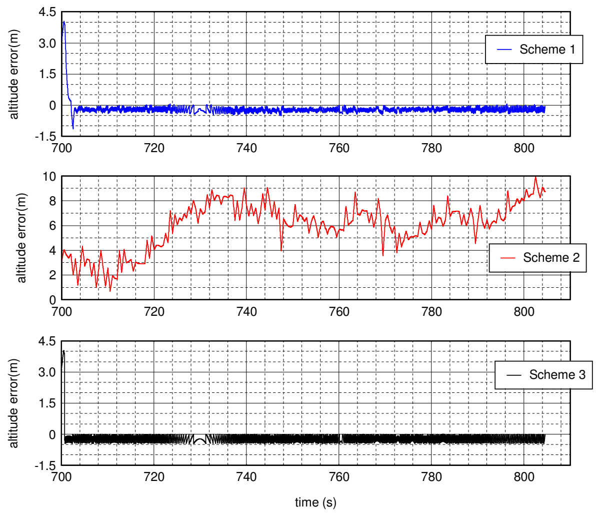


Figure 4b: Nominal case with GPS aiding disabled

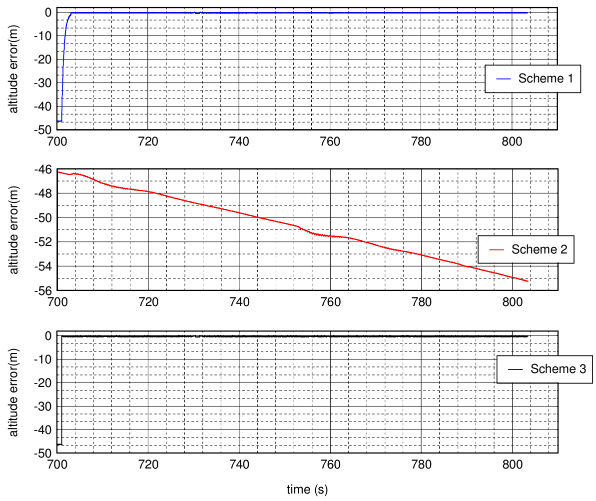


Figure 4c: Intermittent loss in altitude information from RA

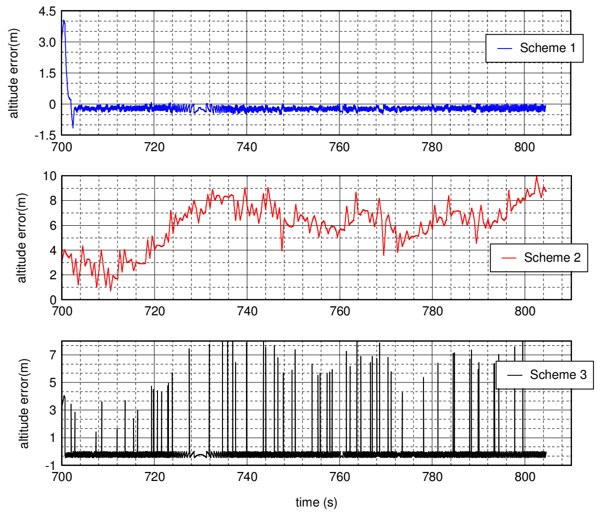
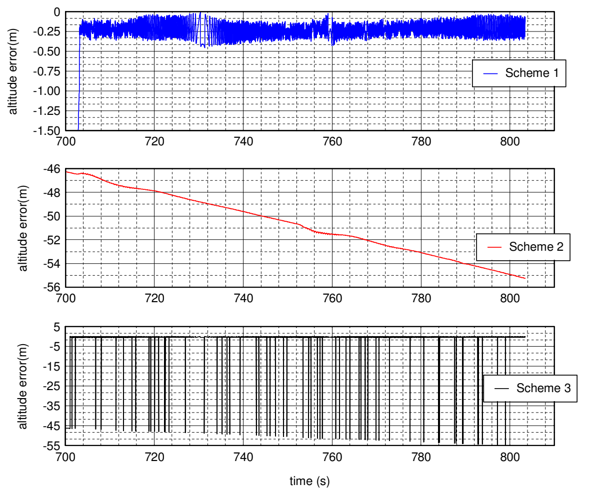


Figure 4d: Intermittent loss in altitude information from RA (with aiding disabled)



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