TEST RESULTS OF A GPS/INERTIAL NAVIGATION SYSTEM USING A LOW COST MEMS IMU

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Abstract

Key Words: MEMS, IMU, INS, GPS

This paper describes the design, operation, and test results of a miniature, low cost integrated GPS/inertial navigation system that uses commercial off-the-shelf Micro-Electro-Mechanical System (MEMS) accelerometers and gyroscopes. The MEMS inertial measurement unit (IMU) is packaged in a small size and provides the raw IMU data through a serial interface to a processor board where the inertial navigation solution and integrated GPS/inertial Kalman filter is generated.

The GPS/inertial software integration is performed using NAVSYS' modular InterNav software product. This allows integration with different low cost GPS chip sets or receivers and also allows the integrated GPS/inertial navigation solution to be embedded as an application on a customer's host computer. This modular, object oriented architecture facilitates integration of the miniature MEMS GPS/INS navigation system for embedded navigation applications and is designed to handle the large errors characteristic of a low grade MEMS IMU.

Test results are presented in this paper showing the performance of the integrated MEMS GPS/inertial navigation system. Data is provided showing the position, velocity and attitude accuracy when operating with GPS aiding and also for periods where GPS dropouts occur and alternative navigation update sources are used to bound the MEMS inertial navigation error growth.

Introduction

The advent of low cost, MEMS accelerometers and gyroscopes offers the opportunity for applying inertial navigation for a wide variety of new applications. This includes navigation and guidance of low cost, small unmanned air vehicles (UAVs) or autonomous ground vehicles (UGVs) such as are shown in Figure 1 and Figure 2. While the principles of inertial navigation are well understood, the challenge when working with the current generation of low cost MEMS instruments is to develop a robust navigation capability that can deal with the large instrument errors experienced with these low grade accelerometers and gyroscopes. The software product described in this paper, InterNav, was developed to include this capability. This paper describes the approach taken for providing inertial navigation with low grade MEMS instruments and presents initial test results showing the type of navigation performance that can be expected using current generation MEMS devices.

Figure 1 Silver Fox UAV[1]

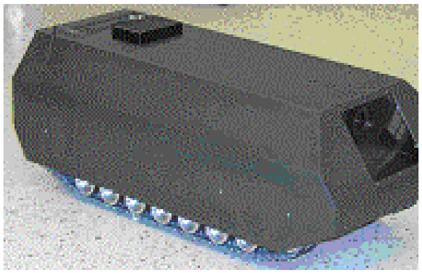

Figure 2 Unmanned Ground Vehicle[2]

Comparison of Inertial Measurement Units and Instrument Performance

In Table 1, a comparison of a commercial off-the-shelf (COTS) MEMS IMU and a low cost COTS Ring Laser Gyro (RLG) IMU is shown. The RLG IMU used for the comparison is the HG1700 produced by Honeywell (see Figure 3). This is available as a commercial unit and has been integrated into a number of different GPS/inertial products produced by NAVSYS[3,4]. The MEMS IMU used for the comparison is the Crista IMU produced by Cloud Cap Technology (see Figure 4). This is built using a triad of Analog Devices accelerometers[5] and gyroscopes[6]. As can be see from the performance figures in Table 1, the instruments used by the Crista IMU, while significantly smaller, lower cost and lower power, are also almost a factor of 100 times less accurate than the HG1700 instruments. While future MEMS technologies promise to provide improved performance levels, approaching those of the HG1700 instruments, the challenge today for low cost navigation applications is to design an integrated system that can perform inertial navigation using these existing low grade MEMS instruments.

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Table 1 IMU Gyroscope and Accelerometer Parameter Comparison

Parameters	UNITS	HG1700[7]	Crista[8]
	Type	*Ring Laser Gyro*	*MEMS*
Size		33 cu in	1.6 cu in
Weight		32 oz	0.7 oz
Power		8 w	0.7 w
Gyroscopes			
Operating Range	±°/s	1000	300
Scale factor accuracy (1 σ)	ppm	150	25000
Scale factor linearity 1 σ to ± 800 °/s	ppm	150	N/A
Bias (1 σ)	°/hour	2	500
Axis alignment stability (1 σ)	µrad	500	3000
Axis alignment stability, non-orthogonality (1 σ)	µrad	100	N/A
Output noise (1 σ of 10,000 samples)	µrad	80	80
Angular random walk max.	°/Rt-hr	0.1	3
Accelerometers			
Operating Range	±g	50	10
Scale factor accuracy (1 σ)	ppm	300	25000
Scale factor linearity (1 σ)	ppm	500	N/A
Bias (1 σ)	mg	1.0	15000
Axis alignment stability (1 σ)	µrad	500	3000
Axis alignment stability, non-orthogonality (1 σ)	µrad	100	N/A
Output noise (1 σ of 10,000 samples)	m/s	0.0024	0.0003[1]
Velocity random walk	(ug/Rt-Hz)	150	400
[1]. Accelerometer includes filtering in sampled signal			

Figure 3 Honeywell HG1700 IMU

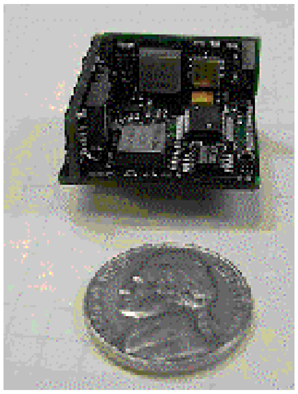


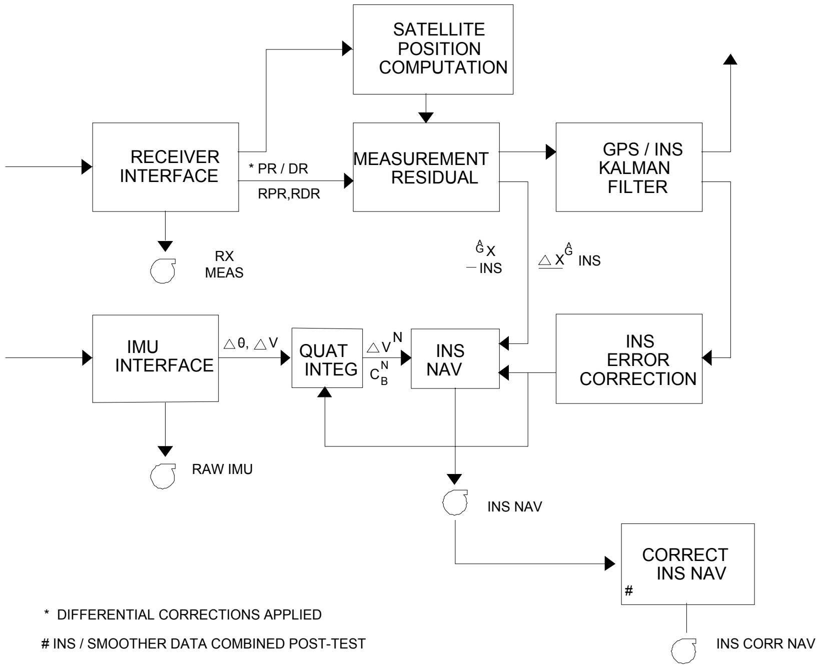
Figure 4 Cloud Cap Crista IMU

InterNav Software

The MEMS inertial navigation integration and testing was performed using NAVSYS' InterNav integrated GPS/inertial software product[9]. InterNav includes the inertial navigation and Kalman filter functions used to combine inertial measurement unit raw data from the gyroscopes and accelerometers ($\Delta\theta$, ΔV) with other sensor data to provide an integrated inertial navigation solution. The software includes the functions illustrated in Figure 5. The inertial measurements are integrated using a quaternion integration algorithm to propagate the inertial states. Periodically, updates are performed to these states to calibrate the the inertial state errors and instruments. A Kalman filter is used to perform these updates.

The InterNav software includes different Kalman filter configurations which are designed to perform both basic alignment of the inertial states, calibration of the inertial errors and advanced functions to facilitate integration with a wide variety of different aiding sources of data. The basic InterNav filter states are shown in Table 2[10]. To align the inertial navigation states, updates are required to observe the initial inertial error state. This is accomplished using a rough alignment mode of operation prior to transitioning to the Kalman filter fine alignment mode. In the rough alignment mode, the initial position, velocity, attitude and rough calibration parameters for the inertial instruments are set. In the fine alignment mode, the filter calculates the best estimate for these parameters using measurement updates from a GPS receiver or other source of aiding information.

The InterNav software is designed to accept inertial navigation updates from a variety of different sources as illustrated in Figure 19. For the purposes of the MEMS IMU performance testing, we used a GPS receiver as the sensor-aiding source. A discussion of how the different sensor inputs can be applied to aid the MEMS inertial navigation solution in the event of GPS dropouts is included in this paper.



* DIFFERENTIAL CORRECTIONS APPLIED

\# INS / SMOOTHER DATA COMBINED POST-TEST

Figure 5 InterNav Software Architecture

Table 2 Basic InterNav Kalman Filter Navigation States

State	Meaning
1-3	Position Error (navigation frame)
4-6	Velocity Error (navigation frame)
7-9	Body Attitude Error (navigation frame) (T_x, T_y, α)
10-12	Accelerometer bias error
13-15	Gyro bias error
16	GPS Clock bias error
17	GPS Clock frequency error
18-26	Accelerometer misalignment & scale factor error
27-32	Gyro misalignment & scale factor error

GPS Aided MEMS IMU Field Test Results

To test the MEMS IMU, we installed it on the GI-Eye test fixture shown in Figure 6. This unit includes the HG1700 IMU, a Novatel OEM-4 GPS receiver and antenna, a camera used as a truth reference, a PC-104 computer stack and associated power supplies and interface circuitry. Data was collected from these components while driving through the test route shown in Figure 7 and Figure 8. The HG1700 integrated GPS/inertial solution has been extensively tested as a TSPI reference system [3] and so was used as the truth reference. The comparison of the position and attitude solutions between the HG1700 and the Crista MEMS integrated navigation solution is shown in Figure 9 to Figure 13.

The GPS-aided Crista solution performed well in observing the position and tilt of the vehicle. As expected, the heading accuracy was much poorer than possible with the HG1700. Our previous testing with the HG1700 has demonstrated alignment accuracies of better than 0.06 degrees (1 mrad) [3]. With the Crista IMU, the heading accuracy was only 2 degrees (35 mrad).

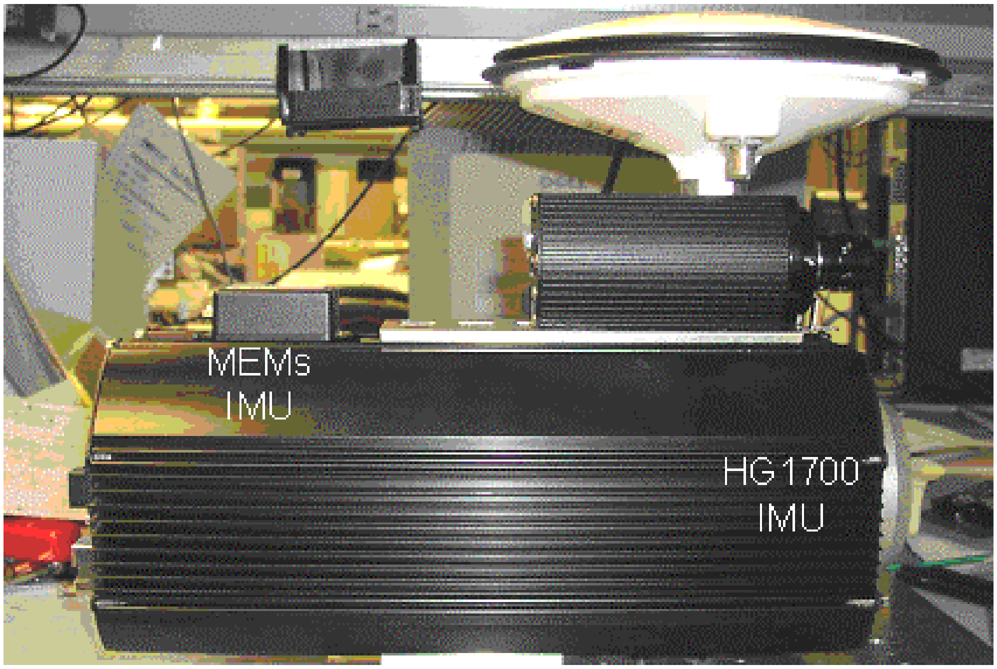


Figure 6 GI-Eye Test Fixture

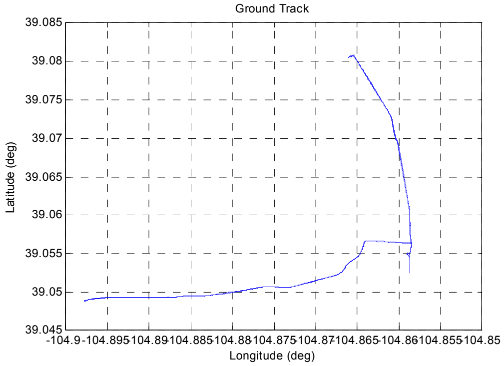


Figure 7 Truck Test Route

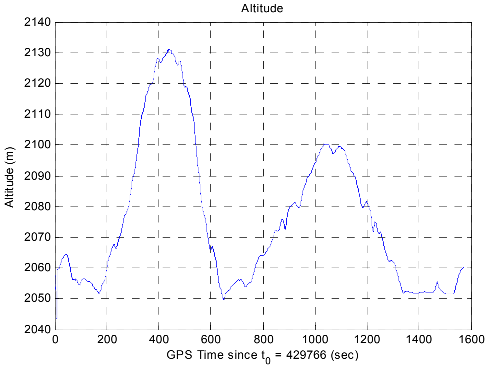


Figure 8 Altitude

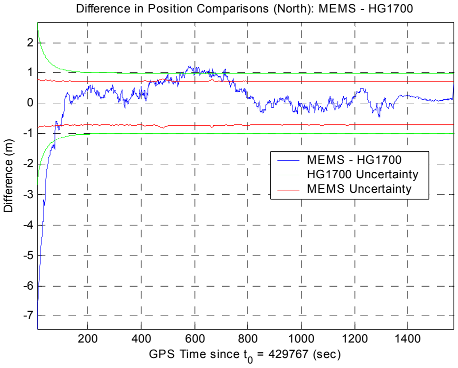


Figure 9 North Position Error

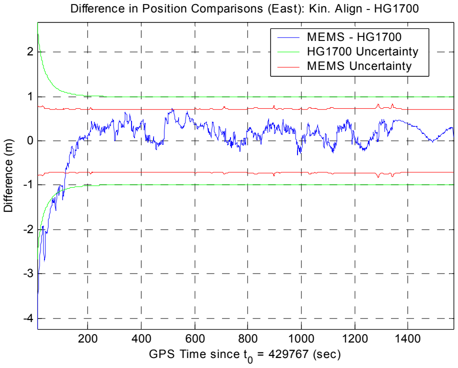


Figure 10 East Position Error

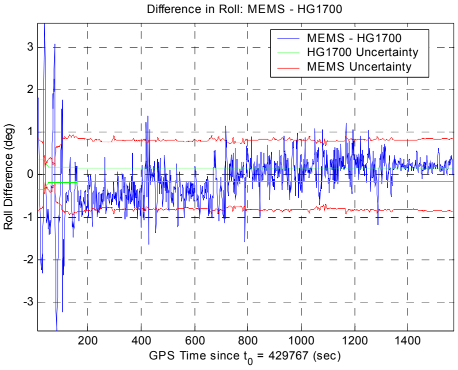


Figure 11 Roll Error

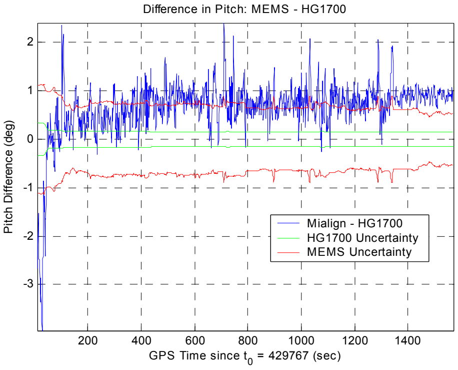


Figure 12 Pitch Error

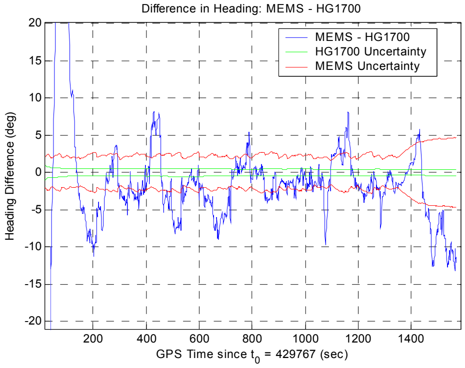


Figure 13 Heading Error

MEMS Inertial Performance Following GPS Drop-Outs

Because of the poor quality of the MEMS inertial instruments, the navigation performance degrades extremely rapidly following loss of the GPS aiding data. To demonstrate this, a GPS dropout was forced (post-test) in the data and the errors on the free-inertial propagated solution was compared against the GPS "truth" solution. The error growth during the dropout period is illustrated in Figure 14 to Figure 17. As can be seen, the position error grows very rapidly without the GPS aiding, exceeding 10 meters within 20 seconds of the start of the drop-out. To maintain navigation performance when GPS is not available, another source of aiding information is essential.

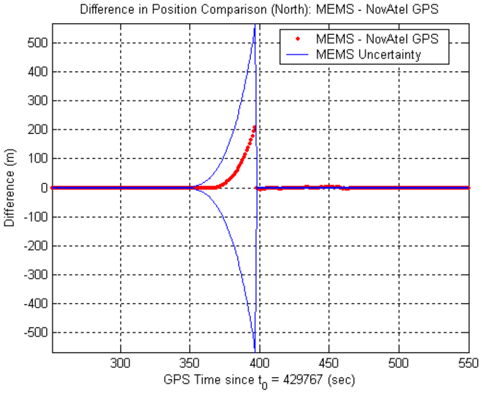


Figure 14 MEMS North position during GPS drop-out

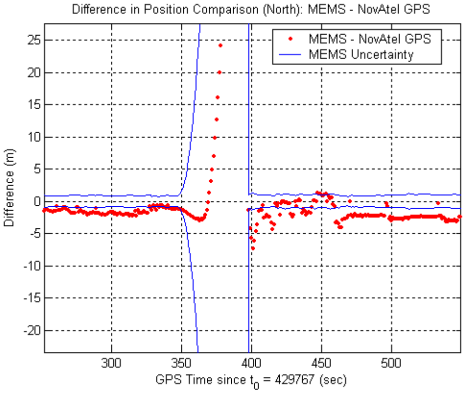


Figure 15 MEMS North position during GPS drop-out (expanded)

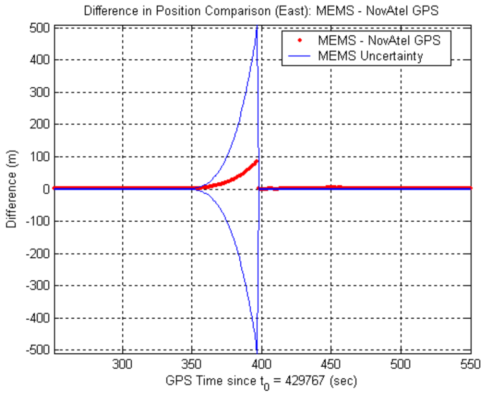


Figure 16 MEMS East position during GPS drop-out

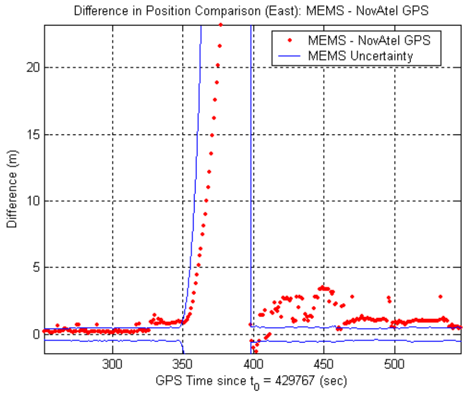


Figure 17 MEMS East position during GPS drop-out (expanded)

Aiding Sources During GPS Drop-Outs

The alternative sources of aiding information that the InterNav software is designed to accept are illustrated in Figure 19 and described below.

Altimeter The vertical error growth in the inertial solution can be bounded by the addition of a baro-altimeter. This provides a measure of the change in altitude which is used as an update by the InterNav software.

Dead-Reckoning InterNav will accept updates from dead-reckoning sensors that can provide speed and heading information. An example of this type of back-up mode would be using a digital magnetic compass integrated with speed data either from an odometer (e.g. in a ground vehicle) or air speed indicator (e.g. in an air vehicle). Applying these updates limits the inertial navigation error drift rates to the accuracy of the aiding data source.

Video Sensor InterNav is designed to accept updates of position offsets and relative motion updates using image processing functions operating on video input data[11,12]. A model generation approach is used to track the motion of objects in images and also observe the inertial derived position offset from reference landmarks, as illustrated in Figure 18. These video updates can also be used to provide position updates and velocity updates to bound the inertial error growth during GPS dropouts.

Communication TOA Updates InterNav is designed to accept time-of-arrival (TOA) updates when they are available from a communications link. As an example, Link-16 provides TOA information that can be used to damp the inertial error growth following GPS dropouts[13]. We are currently implementing TOA aiding within a Software Defined Radio (SDR)[14] that will provide a similar function to perform aiding of the inertial solution following GPS dropouts. In this mode of operation, participating units on the communications network that have access to the GPS signals can augment the performance of units without access to GPS by providing thee TOA updates through their communication links.

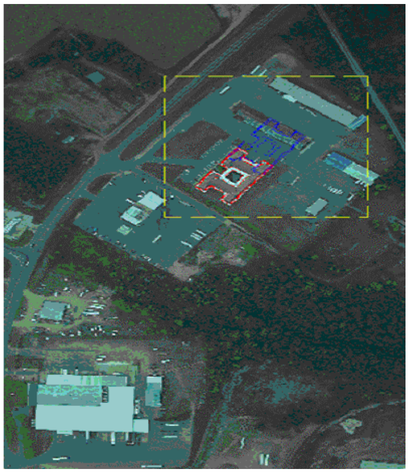


Figure 18 Example of Video Model Offset Detection

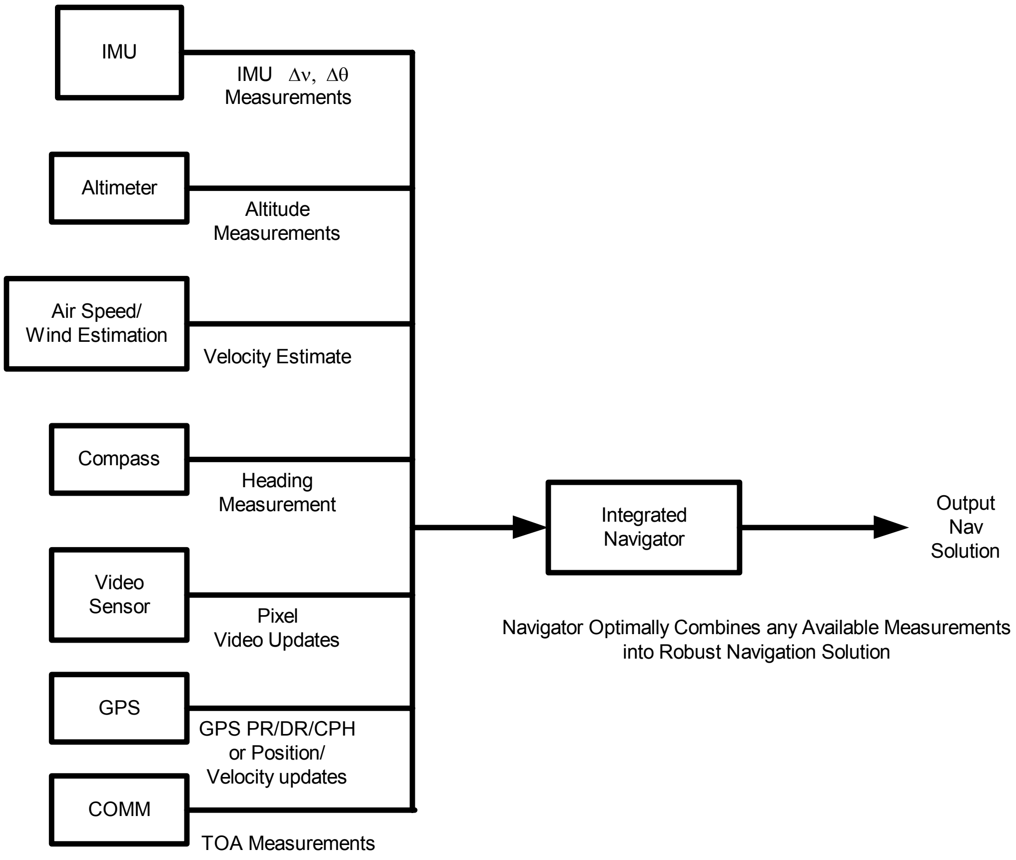


Figure 19 InterNav Alternative Sensor Inputs

Conclusion

In conclusion, our testing has shown that it is possible to perform inertial navigation using a low grade, inexpensive MEMS IMU when GPS aiding is available. The InterNav software includes the capability to observe and calibrate the MEMS inertial errors and can align the inertial navigation solution to provide the vehicle's pitch, roll and heading in support of guidance and control operations.

The low accuracy of the MEMS inertial instruments means that the accuracy of the navigation solution degrades rapidly following loss of lock of the GPS signals. However, InterNav allows other types of navigation updates to also be applied to bound the inertial error growth. The combination of GPS and back-up sensors for inertial aiding, as illustrated in Figure 19, allows inexpensive MEMS instruments to be used as a low cost inertial navigation system.

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