

Utilization of GPS/MEMS-IMU for Measurement of Dynamics for Range Testing of Missiles and Rockets

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ABSTRACT

Missile and rocket test and evaluation centers currently rely on expensive, and at times inaccurate, radar and/or video tracking equipment to provide position, velocity, attitude, and time information of the missiles/rockets during flight test. Additionally, launch scenarios must be limited to locations where radar/video tracking equipment is able to track the missile/rocket through the entire flight.

This paper presents an alternative approach using a small, low cost, integrated GPS receiver and MEMS-IMU embedded in the missile/rocket to provide (via telemeter link) accurate position, velocity, attitude, and time information of the missile/rocket during test flights. An introduction to the problem and the challenges faced in placing a GPS/MEMS-IMU on a small, high g, high roll rate platform is presented. A description of the integrated GPS/MEMS-IMU is presented along with simulated performance results. Finally, the benefits of using the integrated GPS/MEMS-IMU in the test and evaluation environment is discussed.

INTRODUCTION

Range test and evaluation of small missiles and rockets is currently a very costly process that does not always yield time, position, velocity, and attitude measurements to the desired accuracies. Expensive ground based radar and sometimes video equipment are utilized to provide measurements and imagery for evaluation of test firings. The radar system provides moderately accurate time, position, and radial velocity measurements, but attitude must be derived by visual inspection of the slow motion video. Thus, it is difficult to associate the video imagery with the radar measurements to obtain a consistent set of accurate body velocities and attitude.

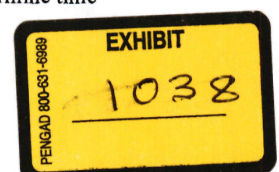
An alternative to this methodology is a concept called Hardened Subminiature Telemetry and Sensor System (HSTSS), a joint effort by U.S. Army Research Laboratory (ARL) and other members of the Department of Defense (DoD) test and evaluation (T&E) community [1]. The HSTSS concept is to place an antenna, battery, transmitter,

sensors and supporting electronics in the warhead section of the weapon under test and transmit data to a ground based receiver. Rockwell was contracted by ARL to develop a top level HSTSS design of a miniature rugged GPS/IMU (Global Positioning System/Inertial Measurement Unit) in accordance with specific performance, space, and power requirements for application to short range, rolling missiles and rockets.

A primary objective of HSTSS is to obtain time, position, velocity, and attitude information, but the capability to integrate additional sensors on-board for transmission of other data of interest is also required. Due to the size of the warhead section, only micro-electro-mechanical systems (MEMS) are feasible as inertial sensors. Because of the relative immaturity of the technology, MEMS inertial sensors have low precision in comparison to inertial sensors of larger size used in existing tactical missile navigation systems. To complicate the problem further, the weapon may undergo high roll rates and high accelerations. MEMS roll gyro scale factor errors and G-sensitivity errors on a rolling airframe are large enough to cause high roll attitude estimation error. Thus, given the current state of MEMS technology, providing navigation adequate for HSTSS is very challenging. Rockwell has developed a top level design for a GPS receiver integrated with a MEMS-IMU to provide an integrated navigation solution. MEMS inertial sensors currently available on the market were identified and modeled in Rockwell's GPS/IMU covariance analysis tool and then analyzed for navigation performance over various trajectories of a 2.75-inch rocket. Study results indicate that current MEMS technology can be implemented to satisfy the HSTSS performance goals, for supplying a real-time navigation solution on-board short range rolling missiles and rockets.

SYSTEM ARCHITECTURE

A diagram of the HSTSS architecture is provided below in Figure 1. During normal operation, GPS signals and IMU data will be collected and processed by the GPS receiver. The GPS will receive inertial data from the IMU and compute a navigation solution which will be filtered with the GPS and magnetic sensor inputs to determine time



space position and attitude information (TSPAI) for the munition. The TSPAI data will be passed to the data acquisition system. The data acquisition system will properly condition and format the data prior to passing it along with external sensor data to the transmitter for transmission out the S-band antenna. The internal power supply of the HSTSS system must provide power to the entire HSTSS system throughout the flight of the missile or rocket.

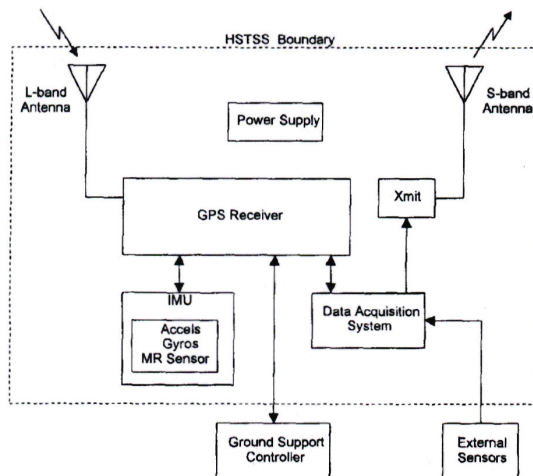


Figure 1 HSTSS Architectural Diagram.

Additional functionality specific to pre-launch activities will be provided through the ground support controller (GSC). The ground support controller will be the user interface through which mission parameters may be initialized and verified after power up. The GSC will also be used during calibration prior to launch.

The entire HSTSS system (including external sensors) must fit into approximately 20 cubic inches of space provided by warhead replacement unit for a 2.75-inch missile or rocket.

MEMS-IMU CONSIDERATIONS

The MEMS-IMU sensors must be capable of meeting the environmental and operational measurement requirements for the missile and rocket vehicles considered for HSTSS application [2,3]. These include large transitions in axial and lateral accelerations (jerk) and angular accelerations during launch and post-launch phases of flight. An extensive survey of the market was performed by Rockwell to identify MEMS inertial sensors that have high potential for integration into an IMU to satisfy HSTSS requirements. A design goal for HSTSS is to utilize

commercial-off-the-shelf (COTS) sensors wherever possible. The results of the survey indicated that there are indeed COTS MEMS inertial sensors available that have high potential for this application. However, there were no gyros found which had the measurement ranges necessary to measure the maximum angular rates specified for HSTSS. Thus, some additional cost would be required to modify an existing gyro design to extend the measurement range.

Sensor specifications obtained from the MEMS sensor vendors during the survey, were used to quantify the errors for covariance analysis, shown in Table 1. It should be noted that some of the vendors did not have the data required to quantify all of the errors, so values specified for analysis in these cases were based on conservative estimates.

Table 1. MEMS inertial sensor errors.

Accelerometer	Gyro
• Initial Bias • Bias In-Run • Initial Scale Factor • Scale Factor In-Run • Bias Temperature Sensitivity • Scale Factor Temperature Sens. • Cross-Axis Sens. • Noise • Misalignment • Misplacement	• Initial Bias • Bias In-Run • Initial Scale Factor • Scale Factor In-Run • Bias Temperature Sensitivity • Scale Factor Temperature Sens. • Cross-Axis G-Sens. • Cross-Axis Scale Factor G Sens. • Noise • Misalignment • Misplacement

The errors listed for accelerometers and gyros in Table 1 are fairly typical for these types of sensors, except for misplacement. Misplacement is the radial distance, r , of the sensor from the roll axis that has angular rotation rate, ω , which causes centripetal acceleration, a_n , to be experienced by the sensor. The centripetal acceleration is normal to the spin axis with magnitude:

$$a_n = r\omega^2$$

This acceleration is measured directly by accelerometers that are mounted with their sensitive axis along a direction radial to the roll axis, and is measured indirectly by the roll axis accelerometer through the cross-axis sensitivity. The gyros are also affected by misplacement through the cross-axis G-sensitivity errors.

GPS/MEMS-IMU PERFORMANCE

As mentioned earlier, the GPS receiver will integrate the IMU data to form a navigation solution. This navigation

solution will then be corrected via a Kalman filter using GPS measurements. A covariance analysis study was performed to determine the potential navigation performance of the GPS/MEMS-IMU configuration.

The dynamics involved in a missile's/rocket's trajectory are extreme compared to typical GPS/IMU platforms. These high dynamics may in turn cause system errors that are normally not observable to become significant factors in the overall navigation error. In order to ensure that the impact of all possible significant error states can be assessed, a fairly complete sensor model was generated for the covariance analysis of the GPS/IMU system. The sensor model developed included states such as: position error, velocity error, attitude error, IMU sensor misalignments, IMU sensor biases and scale factors, IMU sensor temperature sensitivities, and oscillator errors.

Covariance analysis was performed using Missile/Rocket launch scenario data provided by ARL. A typical scenario of a Hydra 70 rocket launch and 8 second flight is shown in Figures 2 through 4. This scenario includes some of the most extreme dynamics that will be found for a missile/rocket. Extremes include a 120 G launch, a 42 Hz spin, and a jerk in excess of 40000m/s^3 . The only extremes this scenario does not include are the lateral Gs that would be found in a maneuvering missile.

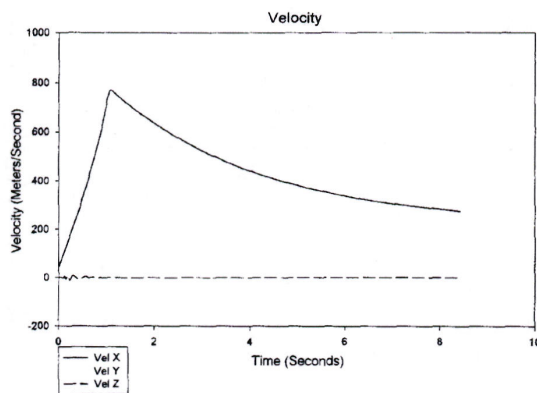


Figure 2. Velocity Profile of Tested Rocket.

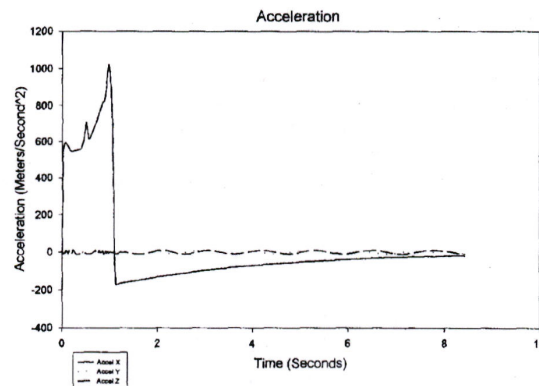


Figure 3. Acceleration Profile of Tested Rocket.

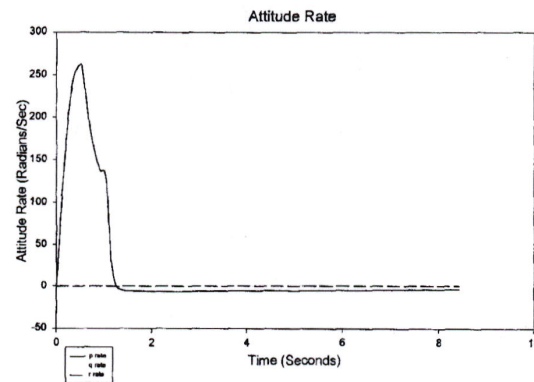


Figure 4. Attitude Rate Profile of Tested Rocket.

It is assumed a prelaunch calibration/alignment procedure will be performed to update the IMU calibration data. The calibration/alignment procedure will also establish initial position, velocity, and attitude prior to launch. Since the IMUs are not of high enough quality to perform full gyro compass alignment (determining heading by sensing earth rate), initial heading and pitch data will be provided to the IMU. Heading and pitch data accurate to about 1 degree will be necessary from instrumentation that will be temporarily mounted external to the missile during the calibration/alignment procedure.

The analysis performed for the Missile/Rocket launch scenario was performed using the following assumptions:

1. The GPS maintains track through launch.

2. The Standard deviation of GPS measurements is 2 meters.
3. Typical satellite geometry (24 satellites in orbit, choosing best 7 satellites visible).
4. No GPS bias error.

Even though measurements from only four GPS satellites are needed to form a complete position solution, the Kalman filter uses measurements from seven satellites in order to reduce the impact of measurement noise on the navigation solution. Since the pseudorange measurements from the satellites are largely uncorrelated, the over determined solution is allowed. The extra data provided by the 3 extra satellites significantly reduces the errors in position and time.

Results of covariance analysis for a GPS/High Quality MEMS IMU system are shown in Figures 5 through 7. Note that when the angular errors get large, the small angle assumptions used by the Kalman Filter are no longer valid.

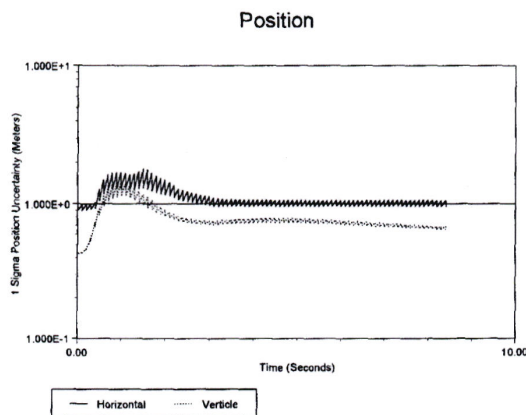


Figure 5. Position Error.

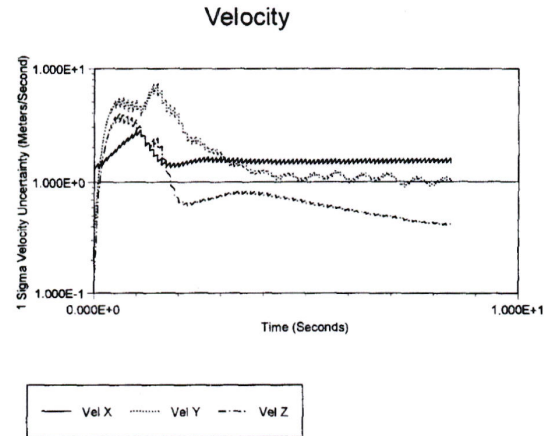


Figure 6. Velocity Error.

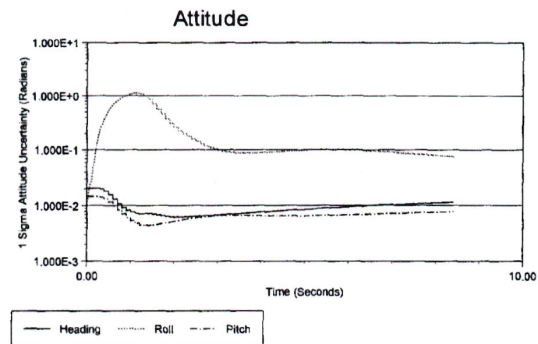


Figure 7. Attitude Error.

GPS/MEMS-IMU PERFORMANCE WITH ROLL AIDING SOURCE

It became apparent from the results of the covariance analysis that the roll error would become too large for all practical IMU configurations. It was therefore decided that a magnetic sensor would be used to provide a roll angle update source for the IMU.

A magnetic sensor built from magnetoresistance ratio (MR) materials was modeled in the covariance analysis tool to provide an additional measurement update to the Kalman filter. The MR sensor measures a component of Earth's magnetic field along the sensor's sensitive axis. Thus, an MR sensor placed on an axis perpendicular to the roll axis provides a voltage output which varies sinusoidally with the vehicle roll angle.

Based on initial assumptions, the measurement noise from the MR sensor was set to a standard deviation of 3 degrees and measurement bias of 3 degrees. Results of covariance analysis for a GPS/High Quality MEMS IMU system with MR sensor updates are shown in Figures 8 through 10. Note that the angular errors of the system are kept in check and thus produce a valid GPS IMU solution.

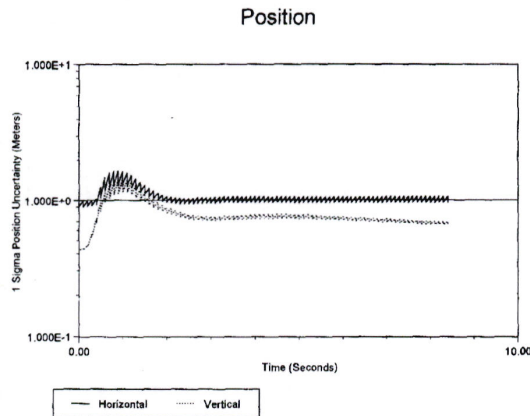


Figure 8. Position Error When Using Magnetic Sensor.

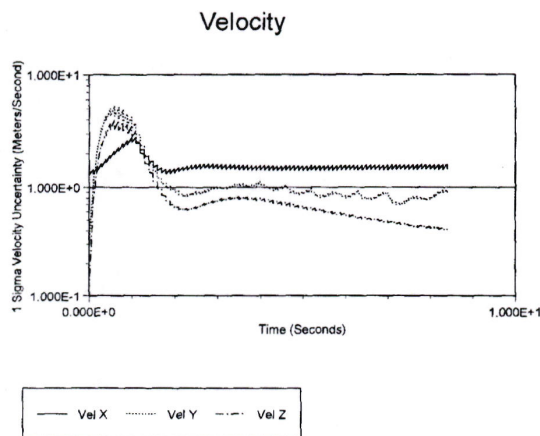


Figure 9. Velocity Error When Using Magnetic Sensor.

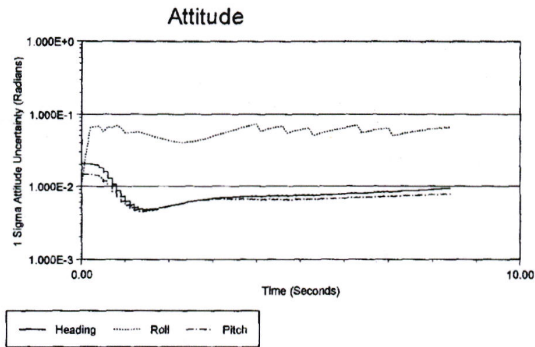


Figure 10. Attitude Error When Using Magnetic Sensor.

CONCLUSIONS

This report has shown that an accurate navigation solution can be achieved using a GPS/MEMS-IMU on-board small short range rolling missiles and rockets.

The benefits that HSTSS provides over the current approach to range testing and evaluation of small missile and rockets are:

1. Significantly reduced cost of testing through a great reduction in required ground support equipment and data analysis.
2. Reduced number of tests required to characterize or verify weapon performance.
3. Ability to test anywhere that sufficient area can be obtained for weapon firing, including over water testing and inland testing in areas where no test ranges exist.

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