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High-Speed Rail IDEA Program

Low-Cost Multiple Sensor Inertial Measurement System for Locomotive Navigation

Final Report for High-Speed Rail IDEA Project HSR-14

Prepared by:
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This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

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Low-Cost Multiple Sensor Inertial Measurement System for Locomotive Navigation

IDEA Program Final Report

for the Period July 1998 Through October 1999

IDEA HSR-14

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National Research Council

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1. EXECUTIVE SUMMARY

Advanced train control systems such as Positive Train Separation (PTS) and Positive Train Control (PTC) require knowledge of the location of a locomotive along the track. They must also be able to detect when the locomotive transfers to a parallel track. This project successfully demonstrated that it is possible to design a low-cost Inertial Navigation System (INS) capable of detecting track switching. The importance (and complexity) of detecting movement to an adjoining track is illustrated by Figure 1. The project also developed algorithms and software for data filtering and navigation for use in the development of a future INS product.

Figure 1. Locomotive navigation systems must not only determine location along a track, but must also detect movement onto a parallel track. (Photo taken during ENSCO IDEA field testing.)

The present project field tested a distributed array of sensors suitable for providing data to an INS. This Multiple Sensor Inertial Measurement System (MSIMS) uses inexpensive MicroElectroMechanical Systems (MEMS) accelerometers (Figure 2), which are configured to provide both linear and rotational data, eliminating the need for expensive gyros. Analysis of the field test data from a rail car demonstrated that it is practical to detect switching to a parallel track using the MSIMS. For future applications, navigation along the track can be performed using the same MSIMS, extended to use Global Positioning System (GPS) or Differential GPS (DGPS) data along with navigation and Kalman filtering software. An Inertial Measurement System (IMS) extended in this way becomes an Inertial Navigation System (INS), capable of providing complete navigation information. This project did not require development of navigation or GPS-integration software. However, ENSCO did independently design and implement full navigation and GPS-aided Kalman filtering for the system. The navigation software development is complete and is presently being checked out and optimized. It will be available for application in a future commercial INS product based on the present project.

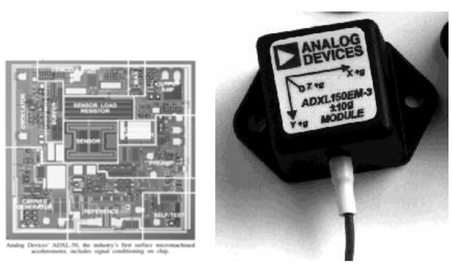


Figure 2. Microphotograph of a MEMS accelerometer, shown next to the three-axis module used for field testing. The accelerometer chip is 0.11 inches square and the module is 1x1x0.75 inches.

The development of the MSIMS began with a requirements-definition phase, in which the system, algorithm, performance, and accuracy requirements, and initial system architecture were determined. The requirements are based on the need to support PTS and PTC applications. These requirements and specifications have been compiled in two documents, the *System Specification for the Multiple Sensor Inertial Measurement System for Locomotive Navigation* and the *Algorithm and Performance Requirements for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*.

Early in the project, we evaluated technology options for sensors appropriate to the application. We found that the type of Analog Devices, Inc. accelerometers identified in the proposal remained the best choice. For the initial proof-of-concept MSIMS, we used Analog Devices Accelerometer Evaluation Modules, Model ADXL150EM-3. We also developed a laboratory evaluation system using individual ADXL150 and ADXL250 accelerometers. In order to record rotational data for algorithm testing, we incorporated three Murata Gyrostar ENV-05D micromachined gyros. We used a 12-bit data acquisition system to record data from the laboratory system for evaluation of the sensors and to provide data for testing and evaluating our sensor, navigation, and Kalman filtering algorithms. LabTech Notebook software was used to simultaneously record inertial data and GPS receiver output. We recorded data on a number of vehicles, including rail cars, automobiles, a van, and an elevator.

We evaluated methods of using multiple accelerometers to increase accuracy. By combining sensors of different resolutions and ranges, the resulting output is superior to that of a single sensor. For example, if a sensor location aboard a locomotive experiences low accelerations at most times, with infrequent short occurrences of high acceleration, then a wide-range sensor and a high-resolution sensor can be used in combination to provide a wide range of measurement, while not sacrificing accuracy at most accelerations encountered by the application. We have simulated the effect of combining sensor data and found a significant improvement over single-sensor data. The effect was also measured under static conditions using the laboratory evaluation system. All sensors used for field testing had the same range, so this effect could not be analyzed using the field test data.

We have developed algorithms for determining acceleration and angular velocity from arrays of accelerometers. We simulated the accuracy of rotational measurements obtained from pairs of accelerometers. We also calculated the accelerations expected from a locomotive switching between two parallel tracks. We then performed simulations that showed the accuracy required for a system of multiple accelerometers to measure acceleration and angular velocity under a variety of conditions. We next evaluated various configurations of accelerometers and three-axis accelerometer modules and determined an appropriate configuration for the MSIMS to be used for field testing.

The field test of the MSIMS sensor array was conducted on 3 August 1999 using the Amtrak 10002 High-Speed Track Geometry Car, seen in Figure 3. The test consisted of data recording for future analysis using four sets of three-axis MEMS accelerometers, mounted in the corners of the car. The Laboratory Evaluation System was mounted in a central location and reference accelerometers were placed at the ends and center of the car. The total data-recording time was approximately 6 hours. The recorded data will be available for future verification of the filtering and navigation software and a portion of the data was analyzed to demonstrate the ability to detect track switching.

Figure 3. Recording data during field test on Amtrak 10002 High-Speed Track Geometry Car.

Analysis of a segment of the field-test data recorded at 30 mph demonstrated that it is possible to detect switching to a parallel track. Further analysis indicated that the tested sensors should be capable of determining the route taken at a turnout at 10 mph or lower. Newly available AXDL105 MEMS accelerometers from Analog Devices, Inc. have five times the resolution of the tested sensors, indicating that positive detection may be possible at speeds of 1-2 mph.

This project produced the following significant findings:

- low-cost MEMS accelerometers are practical for replacing more expensive single accelerometers,
- simulations showed that combining sensors with multiple ranges can provide increased accuracy,
- pairs of accelerometers can be used to measure angular velocity, and
- use of a long baseline to separate accelerometers improves accuracy of rotational measurements.

The MSIMS developed by this project differs in two areas from conventional inertial systems.

- The system uses an array of inexpensive sensors to replace more expensive single sensors.
- The design also reduces cost by using accelerometers separated by a long baseline to replace expensive gyros.

We have designed an MSIMS inertial navigation product and have submitted an IDEA Type 2 proposal to build a prototype system: *Low Cost Multiple Sensor Inertial Measurement Product for Locomotive Navigation*. The MSIMS product will have the following advantages over conventional navigation systems:

- has low cost (initially $2-3000 per unit, depending on configuration),
- has small size, due to use of MEMS accelerometers,
- takes advantage of specialized rail data, including wheel tachometer, transponders, and turnout detection,
- is optimized for railroad applications by making use of one-dimensional nature of railroad track,
- is specifically designed for detecting switching between parallel tracks,
- uses multiple sensors to provide redundancy in case of sensor failure, and
- uses the inertial sensor technology (MEMS) expected to become dominant in the future.

2. IDEA PRODUCT

2.1 PRODUCT DESCRIPTION

The Federal Railroad Administration (FRA) is involved in demonstration projects of advanced train control systems that include a locomotive navigation function. These projects have used conventional rate gyros and laser fiber optic gyros for rate sensors. The technology we have explored in this project has the potential to greatly reduce the cost of locomotive navigation systems while meeting the accuracy requirements of Positive Train Separation (PTS) and Positive Train Control (PTC) systems. Accuracy requirements have specified location to within 20 feet and turnout detection within 50 feet (*1*). The recent North American Joint PTC Program (*2*) requires location accuracy to within 10 feet and speed accuracy within 0.5 miles per hour. One of the major challenges for PTC will be the development of a navigation system sufficiently accurate to meet these requirements.

The Multiple Sensor Inertial Measurement System (MSIMS) designed by this project uses an array of low-cost accelerometers to replace the more expensive sensors used for conventional inertial systems. The MSIMS is the first step toward development of an inexpensive inertial navigation system that meets the requirements for locomotive navigation. The purpose of the MSIMS is to provide inertial navigation information to determine the position and velocity of a locomotive or rail car. For areas with multiple parallel or adjacent tracks, the system must have positional accuracy sufficient to determine the specific track. The future MSIMS product will be designed to accept GPS (Global Positioning System) or DGPS (Differential GPS) data, as well as inertial sensor and wheel tachometer data.

There is an increasing need for smaller and more accurate Inertial Measurement Systems (IMSs) for locomotive navigation, other commercial navigation uses, and for military applications such as guided munitions. Many of these applications are motivated by the present availability of GPS receivers. Although the cost of IMSs has been decreasing due to such inventions as the ring laser gyro and the fiber optic gyro, commercial IMSs can still cost in the tens of thousands of dollars or more. Recent technology advances have produced sensors that are smaller and less expensive, but also less accurate. The most promising development is the introduction of MicroElectroMechanical Systems (MEMS), which are miniature mechanical devices manufactured using techniques similar to those used in the production of integrated circuits. Although individual MEMS sensors do not yet have the accuracy needed for use in commercial IMSs, the IMS accuracy can be increased by combining multiple sensors.

In the original IDEA proposal, we predicted that because many MEMS sensors are being developed for applications such as the automobile industry, we expected the cost to become quite low, perhaps on the order of $5 for accelerometers. The prediction is still on target: In April, Ford Motor Company announced that Analog Devices MEMS accelerometers would be used as crash sensors in more than 15 Year 2000 vehicle lines. Such accelerometers are now available for under $15 in single quantities. (Analog Devices MEMS accelerometers were the sensors chosen for use in our project.) The availability of low-cost miniature sensors provides the opportunity to combine multiple sensors while reducing size and cost in comparison to conventional IMSs.

The MSIMS designed by this project differs in two areas from conventional inertial systems. The system uses an array of very inexpensive MEMS sensors to provide the equivalent performance of much more expensive systems. The design also reduces cost by using accelerometers to replace expensive gyros. An added benefit of using multiple sensors is that the proposed Inertial Navigation System (INS) system, based on the MSIMS, will be able to function even with the loss of one or more of the accelerometer sensors. Placement of accelerometers at locations near the ends of a rail vehicle allows relatively long baselines for sensing rotations. The final INS product will integrate the accelerometer data with DGPS via a Kalman filter to achieve the accuracy needed for this and other vehicle navigation functions. The low cost of MEMS accelerometers allow the system to use multiple sensors of varying dynamic range in each axis, allowing for real-time fault detection and calibration.

The largest benefit of this project is the ability to produce a low cost INS suitable for a number of applications that previously have not considered the use of inertial technology due to cost or performance tradeoffs. In the railroad industry alone, use of low cost INSs can give precise positioning capability to locomotives; specialized maintenance of way vehicles such as tampers, rail grinders, vegetation control vehicles, and rail flaw detectors; track inspection vehicles including track geometry cars, Gage Restraint Measurement System (GRMS) vehicles, and inspector’s hi-rail trucks. There are also numerous military, commercial, and aviation applications for a low cost, accurate inertial navigation system.

ENSCO, Inc. plans to develop a product application based on the MSIMS that uses multiple low-cost MEMS sensors combined with DGPS to achieve the accuracy of a commercial INS. This concept was explored and demonstrated with the present project. We developed a laboratory evaluation system and successfully field tested an MSIMS sensor array using MEMS accelerometers mounted in the Amtrak 10002 High Speed Track Geometry Car. Our analysis determined that location performance should be sufficient for use as a locomotive navigation system in support of advanced train control systems.

2.2 SYSTEM REQUIREMENTS AND ARCHITECTURE

We have developed system requirements and initial system architecture for the prototype system. Accuracy and performance requirements have been documented in the *Algorithm and Performance Requirements for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*. Certain requirements were derived from the *System Requirements Specification for Positive Train Separation (PTS)* by Harris Corp. Advanced Railway Systems (*1*) and the *Project Description* by the Illinois Department of Transportation (*3*). Future development of a product based on this project will also be guided by requirements from the recent North American Joint PTC Program (*2*). We have specified high-level system requirements for the MSIMS in a document entitled *System Specification for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*. The requirements in the document include the performance characteristics of four system states, modes for processing recorded and real-time data, operator commands, physical characteristics, reliability, maintainability, and availability. The document closely follows the DOD-STD-2167A standard. All processing state, algorithm, accuracy, and performance requirements are listed in the following subsections.

2.2.1 Processing State Requirements

- **Navigation State.** The MSIMS will process sensor data from accelerometers and optionally from gyros. In the navigation state, the MSIMS shall (1) accept sensor data and update the calculated position, velocity, and attitude by performing numerical integration of the differential equations of motion.
- **Kalman Update State.** The Kalman filter is updated at a slower rate than the navigation update. In the Kalman filter update state, the MSIMS shall (2) compute a state vector using an observation processing algorithm and a time propagation algorithm.
- **GPS Update State.** GPS data is provided at a slower rate than the Kalman update rate. At each GPS update, the Kalman filter shall (3) accept new GPS or DGPS data and incorporate it into the state vector solution.

2.2.2 Algorithm Requirements

- The algorithms shall (4) accept data with an analog-to-digital conversion resolution of 12 bits.
- The navigation algorithm shall (5) accept and employ acceleration data from MEMS accelerometers.
- The algorithms shall (6) include a vertical channel for acceleration data. The navigation algorithm shall (7) allow the input of constant data or map data for the vertical channel as a substitute for accelerometer data.
- The navigation algorithm shall (8) accept and employ rotational data. The algorithm shall (9) process gyro data or other rotational data provided in the same format of gyro data.
- The rotational data may be calculated from pairs of accelerometers before being input to the navigation algorithm. The algorithms for converting accelerometer data to rotational data shall (10) be provided in the document *Sensor Processing Algorithms for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*. The algorithm will specify whether to filter acceleration first and then calculate rotational data or calculate first and then filter. The converted data may be treated in the navigation algorithm as though it were gyro data.
- Although present plans do not call for the use of gyros, they may be added in the future. If they are added, the navigation algorithm shall (11) employ the rotational data derived from the accelerometers or from a combination of accelerometer and gyro data formed according to a method provided in the document: *Sensor Processing Algorithms for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*.
- Future development, beyond the present contract, may employ additional aiding data such as map data and wheel tachometer distance and speed data to improve navigation accuracy. The navigation and filter algorithms shall (12) be designed so as to allow future modification to allow wheel tachometer data. (Until the method to use map data is determined, no requirements will be based on map data. One possibility is to use map data to replace the vertical channel. Another is to provide rudimentary map data, such as a single track with no curves,

to test map input capabilities or to provide stability in the absence of GPS data. The simplest starting point might be to extrapolate GPS data in a straight line and to use the result to replace any missing GPS data as a substitute for map data. This could evolve into a method of using the GPS Kalman filter inputs for a combined GPS and map solution.)

- The MSIMS shall (13) allow dropping to 1 or 2 axes as an option, perhaps by dropping out input data or using constant input data. This feature will allow comparison of accuracies to determine the optimum sensor configuration.

2.2.3 Performance Requirements

- The inertial data shall (14) be processed at a high enough frequency (approximately 100 Hz) to accurately indicate small-scale position changes (such as caused by switching to a parallel track). Such changes will be determined mainly from the MEMS accelerometer data.
- The Kalman filter shall (15) be processed at a high enough frequency (approximately 10 Hz) to accurately update the state vector solution.
- The GPS/DGPS update shall (16) be performed at a frequency (approximately 0.25 Hz) high enough to provide an accurate state vector, but low enough to avoid problems with correlations in the GPS/DGPS data.
- The implemented algorithms shall (17) perform properly at the processing speeds available from a Pentium 166 MHz or faster computer.

2.2.4 Accuracy Requirements

- The MSIMS navigation design goal shall (18) be to determine locomotive location in direction of motion with 1-sigma accuracy of 20 feet. This requirement is based on the Harris Corp. SRS for PTS, 1995 (*1*).
- The MSIMS location design goal shall (19) be to detect switching between two parallel tracks with 99.999 percent accuracy within 50 feet of travel beyond number 6 to number 20 turnouts and equilaterals at speeds of 0.1 to 125 mph. (Detection at speeds below 10 mph is expected to require additional data, such as wheel tachometer information.) This requirement is based on the Harris Corp. SRS for PTS, 1995 (*1*).
- Position shall (20) be at least as accurate as GPS/DGPS position while GPS/DGPS is available. After a loss and reacquisition of DGPS data, such position accuracy shall (21) be regained within 5 Kalman filter cycles.
- When provided with accurate accelerometer data, the MSIMS shall (22) provide position, velocity, and acceleration data accurate enough to determine lateral location to within 11.5 feet at speeds of 0.1-125 miles per hour or greater for a standard railroad curve or turnout.
- If GPS/DGPS becomes unavailable, the MSIMS shall (23) continue inertial navigation and Kalman filtering. With no GPS/DGPS, data the filter will not enhance the output of the inertial navigation. However, continuing operation of the filter is necessary to give the GPS/DGPS data proper weight if GPS/DGPS is reacquired. Because the inertial sensors have relatively low accuracy, unaided inertial navigation is expected to be accurate for only short time spans. We plan for future versions of the MSIMS to employ additional input data types, such as map information or wheel tachometer data for additional stability and accuracy.

3. CONCEPT AND INNOVATION

This project explored the concept of a low-cost inertial navigation system for locomotives using multiple MEMS accelerometers. We demonstrated that multiple low-cost accelerometers can be combined to produce a system that has lower cost and greater dependability that conventional systems without reducing accuracy. Our methods can be used to produce a commercial product for applications in positive train separation and control.

The innovative elements of the product include:

- use of multiple low-cost MEMS accelerometers to replace more expensive single accelerometers,
- use of pairs of accelerometers to measure angular velocity, replacing expensive gyros, and
- use of a long baseline to separate accelerometers to improve accuracy of rotational measurements.

The final product will have the following advantages over conventional navigation systems:

- has low cost without sacrificing accuracy,
- has small size, due to use of MEMS accelerometers,

- takes advantage of specialized rail data, including wheel tachometer, map information, transponders, and turnout detection,
- is optimized for railroad applications by making use of one-dimensional nature of railroad track,
- is specifically designed for detecting switching between parallel tracks,
- uses multiple sensors to provide redundancy in case of sensor failure, and
- uses the inertial sensor technology expected to become dominant in the future.

The following subsections discuss the advantages of using MEMS sensors, the increase in accuracy from using multiple sensors, and the methods of using pairs of accelerometers to replace gyros. They also describe the advantages of using an inertial navigation system designed specifically for railroad applications.

3.1 MEMS AND OTHER INEXPENSIVE SENSORS

Present MEMS sensors are at least 10 to 100 times less accurate than the corresponding components in commercial IMSs. In the course of the project, we developed methods of combining sensors to increase the accuracy of the MSIMS. Because simple averaging or filtering techniques cannot reduce random errors by more than the square root of the number of sensors, a satisfactory general-purpose multiple sensor IMS would require from 100 to 10,000 MEMS per axis. Instead of combining identical sensors to improve accuracy, we developed a number of practical methods that work together to reduce the number of sensors required to produce a satisfactory IMS. These methods were used to design a general-purpose IMS whose performance was optimized for this specific application. Our project included a laboratory evaluation system using sensors with different sensitivities for two of the axes. In general, an optimal configuration for a specific application provides axis-dependent accuracy and may allow individual sensors to contribute to more than one axis.

The goal of this IDEA Program effort is to develop a commercial IMS using low-cost sensors. The technology of recent sensors is described below, followed by presentation of the techniques used to develop the low-cost MSIMS. MEMS is an emerging technology that promises to revolutionize measurement and control, just as the introduction of integrated circuits revolutionized electronics. MEMS sensors are miniaturized devices that can be batch-fabricated by techniques similar to those used for semiconductor manufacture. MEMS sensors can be fabricated on the same silicon substrates as semiconductors, allowing the support electronics to be integrated on the same chip. The concept of an integrated micromachined sensor was first proposed in 1984 (*4*).

MEMS devices are generally classified as either actuators or sensors. Only the sensors appear to be useful for the IMS in this effort. MEMS sensors generally use piezoelectric, piezoresistive, or capacitive methods. Present MEMS sensors suffer from offset and temperature dependencies, which can limit the accuracy at low frequencies. Low-cost accelerometers and gyros (including non-MEMS devices) are discussed below.

3.1.1 Accelerometers

Accelerometers typically contain a mass suspended by a flexible mechanism such as a spring or arm. The acceleration of the device is determined by the movement or location of the mass, the force on the restoring mechanism, or the internal force required to keep the mass in a fixed position. To date, there has been a great deal of research on MEMS accelerometers, but relatively few commercial products. The first major application for MEMS accelerometers is expected to be the automotive industry. Accelerometers are used to determine air bag deployment and are expected to find increased application in active suspension systems, antilock brakes, and ride-control systems. Micromachined accelerometers are predicted to have greater reliability and much lower cost than present mechanical or piezoelectric accelerometers used in the auto industry. They can also have built-in self-test and calibration features since electrostatic fields can be generated to deflect the seismic mass by precise amounts.

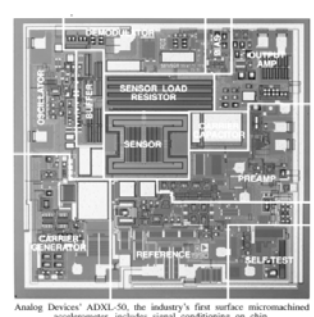


Figure 4. Full Die Photo of Analog Devices ADXL50 accelerometer.

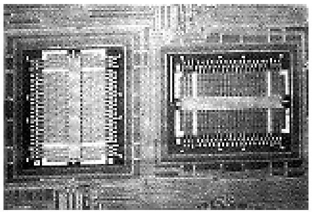


Figure 5. ADXL250 Two-Axis Accelerometer used in ENSCO Laboratory Evaluation System.

The ENSCO field test for this project used MEMS accelerometers from Analog Devices for both the field system and the laboratory evaluation system. The accelerometers are complete acceleration measurement systems, including signal conditioning circuitry, each fabricated on a single chip (*5*). The devices are extremely shock and vibration resistant, and have even been used by the Army Research Laboratory (ARL) to instrument artillery shells, which have been fired without damaging the accelerometers (*6*). As an example, Figure 4 shows the ADXL50, which is an early Analog Devices accelerometer system. The sensor is located in the center of the chip, which is approximately 0.11 inches square. The ENSCO field test used the ADXL150 and ADXL250 accelerometers, which have similar architecture and improved performance. The ADXL250 is a complete two-axis accelerometer on a single chip. The dual sensors on the chip are shown in Figure 5. The ADXL250 has a 5-g to 50-g range and a 74 dB signal -to-noise ratio at 100-Hz bandwidth. For the field test, the bandwidth was filtered to 10 Hz to provide anti-aliasing and greater signal-to-noise ratio. The laboratory evaluation system (also used to supplement the MSIMS in field testing) used ADXL250's for the horizontal axes and an ADXL150 for the vertical axis. Two ADXL250's were used for testing the concept of using multiple sensors to improve range and accuracy. The field system used four packaged ADXL150EM-3 modules produced for Analog Devices by Crossbow Technology Inc. (Figure 6). The ADXL150EM-3 uses three ADXL150 sensors for three-axis sensing. Analog Devices has recently introduced the ADXL105, which has five times the sensitivity of the ADXL150/250. Three-axis ADXL105-EM3 modules are now available. We expect our future MSIMS product application to be based on ADXL105 technology.

Figure 6. Analog Devices three-axis measurement system used in ENSCO field testing.

3.1.2 Gyros

MEMS gyros have been produced in laboratory settings and commercial units are rapidly approaching general availability. Most rely on the principle that vibrating elements will change frequency due to the Coriolis effect when the device is rotated. An example, from Analog Devices, is shown in Figure 7. Rotating MEMS gyroscopes have been designed and their rotors have been built and tested (*7*), but they are not expected to be commercially available in the near future. A number of inexpensive non-MEMS vibrating gyros are already available commercially. For example, Murata (Figure 8) manufactures the inexpensive (order of $25 in quantity) ENC-03 Gyrostar piezoelectric ceramic gyroscope. However, the performance is too poor for IMS use, even with an array of sensors. It has an estimated (not given in specification sheets) 5 deg/s linear drift (*8*). Murata also makes the ENV-05 Gyrostar, which is more suitable for IMS applications. It has 0.1 deg/s resolution and a 20-mV noise level. During the project, ENSCO added three ENV-05 gyros to the laboratory evaluation system to obtain a complete six-degree-of-freedom sensor system. The Systron Donner Quartz Rate Sensor (formerly "GyroChip") uses a micromachined quartz tuning fork and includes all support electronics. Models are available with ranges from ±50 to ±1000 deg/s. For these models, the resolution is 0.004-0.04 deg/s, bias stability is 0.002-0.02 deg/s short term and 0.2-2.0 deg/s long term. The present cost is prohibitive (order of $2K) for use in arrays for inexpensive IMSs in the $1-2K range. A less expensive (order of $1K), but also less accurate, GyroChip II is available (bias stability 0.05 deg/s short term and 1.0 deg/s long term with range of ±100 deg/s). Draper Laboratory (*9*) has developed MEMS tuning fork gyros over

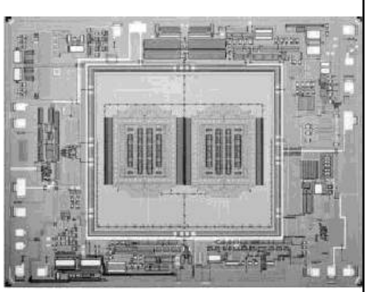


Figure 7. MEMS gyro under development by Analog Devices, Inc.

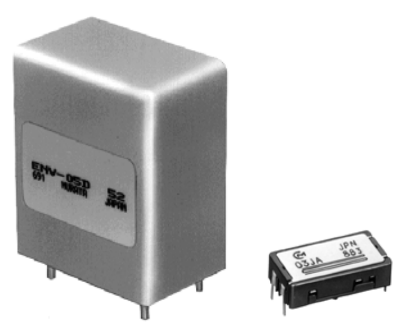


Figure 8. Murata ENV-05 and ENC-03 Piezoelectric Gyros.

the past eight years. Resolution has steadily improved by roughly a factor of 10,000 over that time period. Recent units represent the state of the art and have averaged below 10 deg/hr resolution (*10*). Relatively inexpensive MEMS gyros may soon be available from Analog Devices, who has announced development, but gives no estimated date for a commercial product (*11*). The Analog Devices chip is shown in Figure 7.

No presently available MEMS gyros or inexpensive miniature gyros appear to be suitable for use as the sole source of rotational data in practical IMSs. However, we found that they can be used in combination with other sensors to provide data more accurate than obtainable from single sensors. We will show, below, that pairs of accelerometers can be used as rotational sensors to augment or replace gyros. Our field testing has shown that angular velocity with acceptable accuracy can be obtained from pairs of accelerometers alone without the need for gyros.

3.2 MULTIPLE SENSORS

3.3 Combining Sensors with Different Characteristics

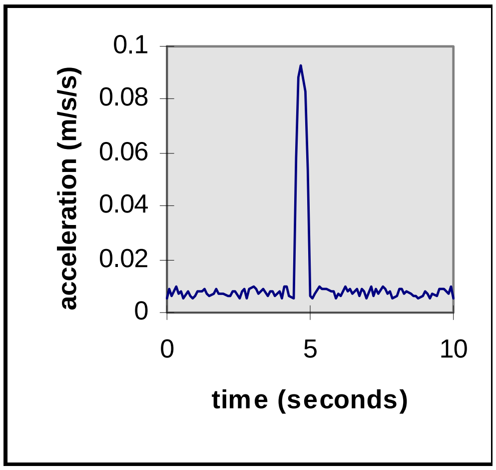


Figure 9. Simulated acceleration.

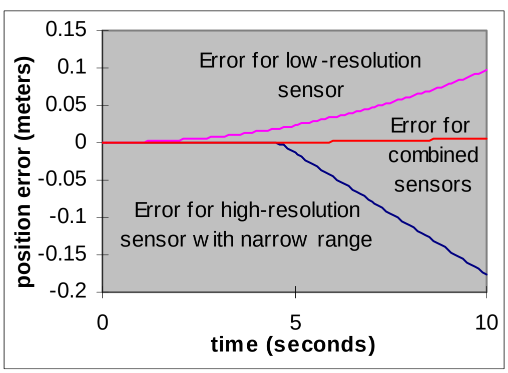


Figure 10. Accuracy of combined sensors.

By combining sensors of different accuracies and ranges, the resulting output is superior to that of any single sensor type. For example, assume that a particular IMS application has low accelerations at most times, with infrequent short occurrences of high acceleration. A wide-range sensor and a high-resolution sensor can be used in combination to provide a wide range of measurement, while not sacrificing accuracy at most accelerations encountered by the application. We have simulated the effect of combining sensor data and found a significant improvement over single-sensor data. The following example uses 10 seconds of simulated acceleration that is below 0.01 m/s^2 except for a 0.5-second interval, as shown in Figure 9. For this hypothetical example, we assume that we have two accelerometers. One has a range of ± 5 m/s^2. Its resolution of 0.004 m/s^2 is simulated by adding random numbers in the range 0 to 0.004 m/s^2 to the acceleration values. The result simulates both noise and drift at the measurement threshold level. For purposes of illustration, the second sensor has a resolution of 10^{-8} m/s^2 with a range of $\pm 10^{-2}$ m/s^2. It provides accurate output, except during the period of high acceleration, for which the output is the limiting value of 10^{-2} m/s^2. Its resolution is simulated by adding random numbers in the range 0 to 10^{-8} m/s^2 to the acceleration values, resulting in negligible noise and drift in the present calculation. The data from the two sensors can be combined by using the capacitive sensor data for times when it is higher than the tunneling-tip sensor limit of 10^{-2} m/s^2 and using the more accurate tunneling-tip sensor data at all other times. Our calculations for the error in position for each sensor and for the combined data are shown in Figure 10. The plot shows that a significant improvement is obtained by combining the sensor data. The values chosen for the present example were for illustration only. We have also performed simulations using combined sensors with the resolutions of presently available MEMS sensors. The results are presented later in this report.

3.3.1 Using Accelerometers as Gyros

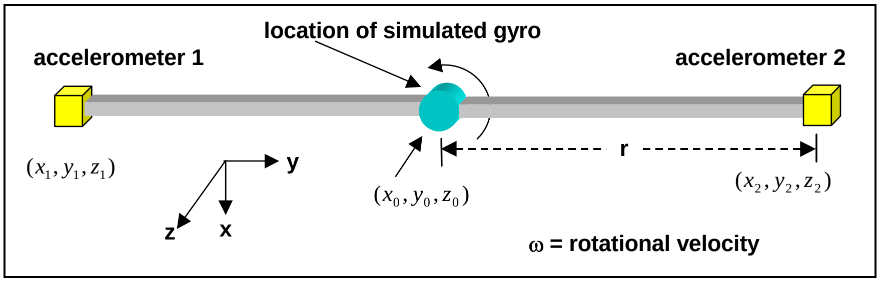


Figure 11. Use of two accelerometers to replace a gyro.

The most costly hardware components of an inertial measurement system are the gyros. Ring Laser Gyros (RLGs) or Fiber Optic Gyros (FOGs) are less expensive than earlier mechanical gyros, but nevertheless typically cost in the tens of thousands of dollars or more. A major cost saving can be realized in the design of an inertial measurement system if inexpensive replacements can be found for these gyros. In our project, we analyzed the rotations that must be measured to determine the direction taken at a turnout. We also considered the rotational accuracy required for navigation of a vehicle constrained to a single degree of freedom of motion along a track. We concluded that sufficient accuracy could be achieved by using pairs of sensitive accelerometers, as illustrated in Figure 11.

We determined practical locations for accelerometers used to measure rotational motion. We found that nine accelerometers in six locations was the simplest (although not necessarily the most practical) configuration that would allow measurement of all linear and rotational components of motion in three dimensions, including both angular velocity and angular acceleration. An example of such an arrangement is shown in Figure 12. The diagram indicates only the orientation of the sensors. For a practical application, the sensors would be attached to the locomotive and more suitable locations would be chosen.

Nine accelerometers are needed because angular acceleration can be measured using the orientations shown in Figure 13, while angular velocity is measured as shown in Figure 15. The two measurements are independent for a particular axis of rotation and can be used to supplement each other. The accuracy of the angular velocity, integrated from measurements of angular acceleration, is shown in Figure 14.

For the configuration shown in Figure 15, the magnitudes of the angular velocities can be determined from

$$\begin{bmatrix} \omega_x^2 \\ \omega_y^2 \\ \omega_z^2 \end{bmatrix} = -\frac{1}{2X_1Y_2Z_3}\begin{bmatrix} Y_2Z_3 & X_1Z_3 & X_1Y_2 \\ Y_2Z_3 & X_1Z_3 & X_1Y_2 \\ Y_2Z_3 & X_1Z_3 & X_1Y_2 \end{bmatrix}\begin{bmatrix} a^{(1)}{}_x \\ a^{(2)}{}_y \\ a^{(3)}{}_z \end{bmatrix}. \quad \text{where} \quad \begin{aligned} X_n &= x_n - x_0 \\ Y_n &= y_n - y_0 \\ Z_n &= z_n - z_0 \end{aligned}.$$

for (x_0, y_0, z_0) at the coordinate center. Here, the superscript on the accelerations ($a^{(1)}x$, $a^{(2)}y$, $a^{(3)}z$,) indicates the sensor location and the subscript indicates the measurement axis. For certain motions, more accurate angular velocities can be obtained by integrating the angular accelerations, which are determined from

$$\dot{\omega}_x = a_z^{(\text{y axis})}/Y - \omega_y\omega_z, \qquad \dot{\omega}_y = a_x^{(\text{z axis})}/Z - \omega_x\omega_z, \qquad \dot{\omega}_z = a_y^{(\text{x axis})}/X - \omega_x\omega_y.$$

For low angular velocities, this integrated result is more accurate than the direct calculation of angular velocity. After initialization, it can be used to determine the sign of the angular velocity. However, the direct calculation of angular velocity provides a more stable result than obtained from angular acceleration, since errors accumulate when integrating angular acceleration over long time periods. It does not, however, determine the sign (direction) of rotation. To avoid drift in the calculated value of angular velocity, it will be calculated as a weighted average of the measured and integrated values of angular velocity. The average has the advantage of avoiding buildup in error of the integrated result.

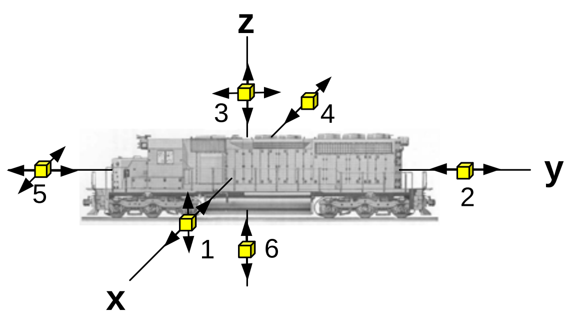


Figure 12. Nine accelerometers for measuring linear acceleration, angular acceleration, and angular velocity.

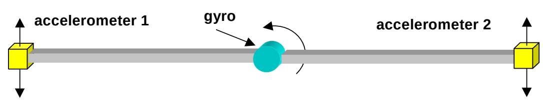


Figure 13. Orientation of accelerometers for measuring angular acceleration.

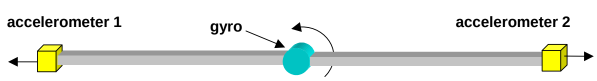


Figure 15. Orientation of accelerometers for measuring angular velocity.

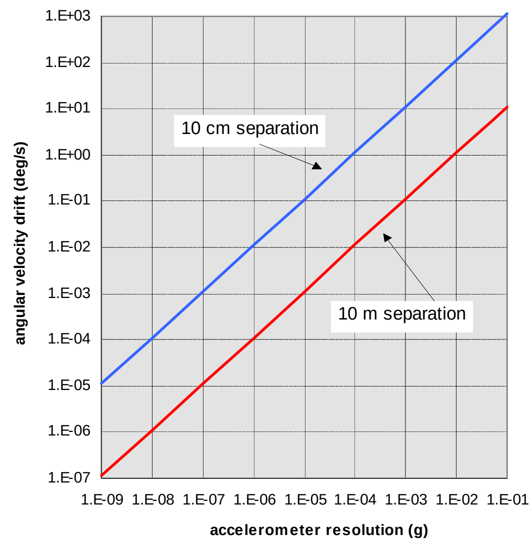


Figure 14. Accuracy of rotational velocity, integrated from measurements of angular acceleration, as a function of accelerometer accuracy.

To determine the signs (directions) of the components of angular velocity, we need to know the initial conditions of the system. If the system is at rest, then the terms involving ω will be zero, and the sign of subsequent angular velocity will be determined by the initial angular acceleration. If the initial state is one of rotation, then the direction must be known in order to be able to solve for the angular accelerations. Once the initial conditions are known, the equations can be solved for all subsequent motion. The reason nine accelerometers are required is to simultaneously measure linear acceleration, angular velocity, and angular acceleration.

For practical use within a locomotive, it is possible to improve on the configuration shown in Figure 12. Our goal is to reduce wiring and maintenance by reducing the number of sensor locations. Because the accelerometers are relatively inexpensive, it is more practical to reduce the number of sensor locations by using four three-axis accelerometer modules, configured as shown in Figure 16. Three-axis modules are readily available and are convenient to use. This is the configuration that was used for field testing in the Type 1 IDEA project, with sensor modules attached inside the 10002 Track Geometry Car.

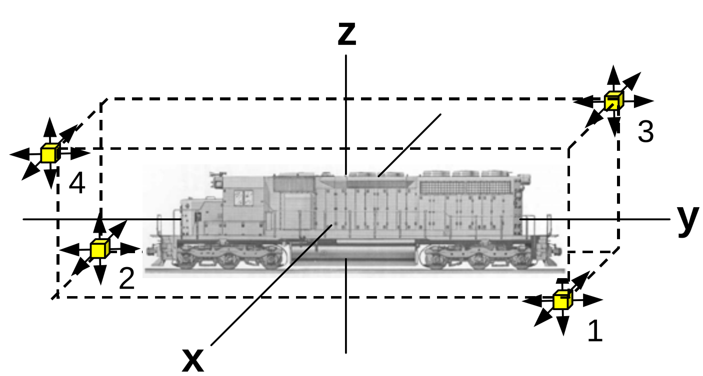


Figure 16. Twelve accelerometers for measuring linear acceleration, angular acceleration, and angular velocity.

We can see that the acceleration at any positive or negative coordinate axis can be determined by averaging two modules at diagonal corners of the rectangle intersecting the axis. Hence, we can use the same equations as before

to determine the linear acceleration, angular acceleration, and angular velocity. By using three-axis modules, we have additional freedom for automatic correction of errors in orientation through calibration procedures.

3.3.2 Advantages of Multiple Sensors

As described in the two sections above, more than one sensor per axis can be used to combine sensors with different characteristics or to measure rotation with accelerometers. Another, more basic, reason to increase the number of sensors is to reduce random error. Because simple averaging or filtering only decreases the error by the square root of the number of sensors, only modest gains in accuracy can be obtained in this manner. However, as sensor size, power requirements, and price decrease, a greater number of devices can be used by having multiple sensors per chip and by mounting chips directly on the circuit board. As greater numbers of low-cost sensors are used, the possibility of sensor failure increases. Because of the redundancy in the multiple sensors, fault detection techniques can be used to isolate faulty sensors. Future implementations of the filter will be designed to minimize the effect of dropping faulty sensors from the solution.

4. INVESTIGATION

4.1 ALGORITHMS

4.1.1 Filter Algorithms

We have developed algorithms for navigation and filtering. This project did not require development of navigation or GPS-integration algorithms or software. However, ENSCO did independently design and implement full navigation and GPS-aided Kalman filtering for the system. The navigation software development is complete and is presently being checked out and optimized. It should be available for application in a future commercial INS product based on the present project. These algorithms are provided in an internal ENSCO document entitled *Algorithms for Kalman Filter Aided Inertial Navigation*. Algorithms are in sufficient detail to allow the navigation and filtering software algorithms to be developed directly from the document.

The navigational and filtering elements are central to the MSIMS. They process input sensor and DGPS data and provide smooth position and orientation outputs. A Kalman filter is also ideal for integrating inputs from sensors with differing characteristics. As our starting point for a commercial product, we plan to use the Kalman filter developed in this project and extend it to support wheel tachometer data, truck angle sensor data, and binary location data from transponders and turnout detectors. Figure 17 shows a block diagram of the proposed DGPS-aided navigation and Kalman filtering system. The shading indicates components developed during the present project and the other components are proposed for a Type 2 project.

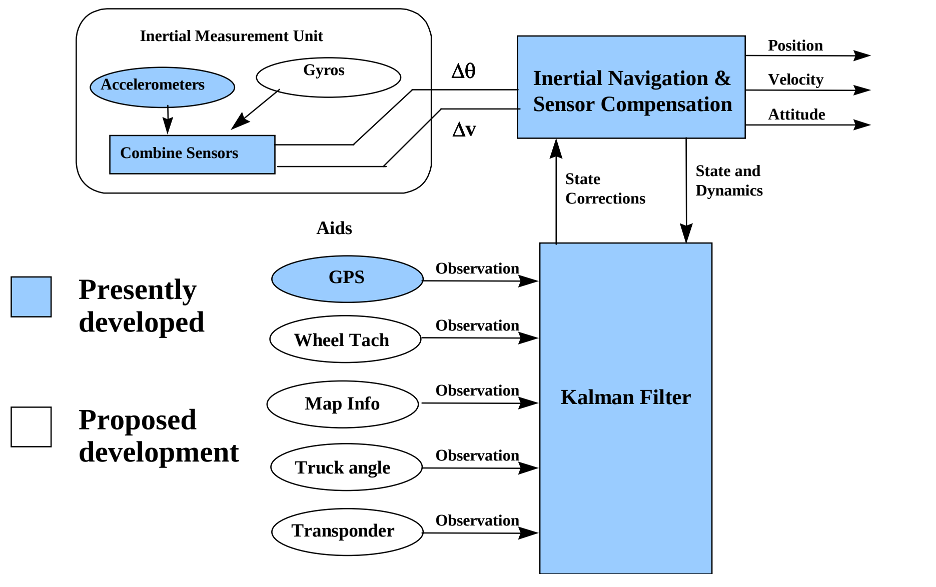


Figure 17. Configuration for navigation and GPS-aided Kalman filtering.

For checkout and future testing of the navigation and Kalman filter software, we have recorded data for a variety of vehicles using the laboratory evaluation system. We have recorded several 20-minute automobile trips using GPS (Delorme Tripmate and Garmin GPS12XL) and six-degree-of-freedom inertial data. We also recorded railroad data from the most readily available source in central Florida: the steam locomotive that travels around the perimeter of the Magic Kingdom at Disney World. (This data recording did not make use of IDEA funding.) The railroad data includes GPS (Garmin GPS12XL) and 8-channel inertial data (six degrees of freedom) using the laboratory evaluation system. We recorded data using LabTech Notebook and modified the laboratory evaluation system software to combine inertial and GPS data into the correct format for testing the navigation and Kalman filter software. We also recorded specific bench-testing static and rotational data for evaluating the navigation and Kalman filter algorithms. The field test provides approximately 6 hours of simultaneous data from 12 MEMS accelerometers, 7 reference accelerometers, 2 reference gyros, an automatic location detector, and the laboratory evaluation system with 5 accelerometers and 3 gyros.

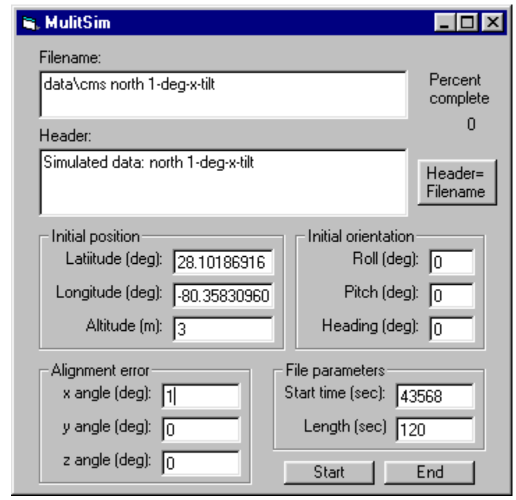


Figure 18. Simulation of data for testing navigation and Kalman filtering software.

We have used the recorded laboratory data to check out and debug the navigation and Kalman filter software. Over the past few months we have uncovered and corrected a number of problems with the algorithms and software. The most recent problem was described at the second Panel Meeting, held on 13 October 1999. The filter exhibited a saw-tooth pattern in the velocity. This problem has been investigated and found to be a numerical error in the Kalman filter propagation matrix. After the error was corrected, the filter showed essentially perfect behavior when presented with simulated data having no noise or bias. Results are greatly improved with the recorded inertial data, but we must now readjust a number of parameters for proper performance. In addition, our hardware alignment procedures for the laboratory evaluation system must be improved to provide adequate test data. We will continue to address both areas, using company resources after the end of the project. We are investigating these and other possibilities by using simulated data, for which we know the exact response expected from the filter. Our filter development has not directly affected our analysis of field test data, which involves only sensor data and does not require the filter software. We have begun development of a simulation program, shown in Figure 18. The development of navigation and GPS-aided algorithms and software has been an ENSCO activity, not required by the IDEA contract, and we intend to continue the development and checkout after the end of the contract.

4.1.2 Sensor Algorithms

We developed the algorithms for sensor processing. These algorithms are provided in an internal ENSCO document entitled *Sensor Processing Algorithms for the Multiple Sensor Inertial Measurement System for Locomotive Navigation*. Algorithms were developed for combining sensors with different characteristics and for calculation of rotational data from accelerometers in three dimensions. Configurations were developed and optimized for location of sensors over long baselines in three dimensions.

4.1.3 System Software

We developed software that implements the navigation and Kalman filtering algorithms. The processing algorithms are coded in Fortran using the Microsoft Fortran PowerStation. Coding has been completed and the software is being checked out. The software consists of 32 routines, with 4248 total lines (including comments and spacing) and 1841 lines of code. Table 1 lists the file names of the software modules, the total lines, lines of comments, and lines of code. Preliminary results from testing the program were described in Section 4.1.1.

File Name	Total Lines	Comments	Code	File Name	Total Lines	Comments	Code
A_plus_B	75	30	22	N_matrix	102	34	39
A_minus_B	70	26	21	Navigation	282	80	142
A_x_B	84	30	29	PHI_matrix	196	46	119
AT_x_B	84	32	29	Propagate_P_matrix	131	45	60
MATRIX_x_VECTOR	86	27	31	PROPAGATE_S_V	78	29	25
C_matrix	132	48	56	R_ALT	96	35	38
Chi_Square	169	45	84	R_HOR_MATRIX	111	35	52
Gradient_Gravity	75	43	13	Read_Data	132	35	67
H_Hor_matrix	65	22	23	RESIDUALS_ALT	53	25	12
INIT	235	56	136	RESIDUALS_HOR	76	26	32
K_MATRIX	96	30	40	SCALAR_x_MATRIX	75	30	22
KALMAN	300	87	132	Sensor_Compensation	269	44	142
M_matrix	106	38	40	Skew_Symmetric	71	30	19
MAIN	303	96	124	Update_A_matrix	153	61	65
MATRIX_T__x_VECTOR	73	24	25	Update_Position	169	71	69
A_x_BT	83	30	29	Update_Velocity	218	49	104
Totals				32 Routines	4248	1339	1841

Table 1. Software Modules.

4.2 SENSORS

Sensors were selected and purchased for laboratory measurement and testing and for the field-tested MSIMS system. For the field testing, we chose three-axis Analog Devices Accelerometer Evaluation Modules, Model ADXL150EM-3. For laboratory testing, we obtained Analog Devices ADXL150 single-axis accelerometers and ADXL250 two-axis accelerometers. We also purchased three Murata Gyrostar ENV-05D gyros for use in the laboratory evaluation system.

4.3 SIMULATIONS

We have used both actual and simulated data to test the navigation and Kalman filtering algorithms. An example of our sensor and data simulations is shown in Figure 19. The first panel shows the simulator used to

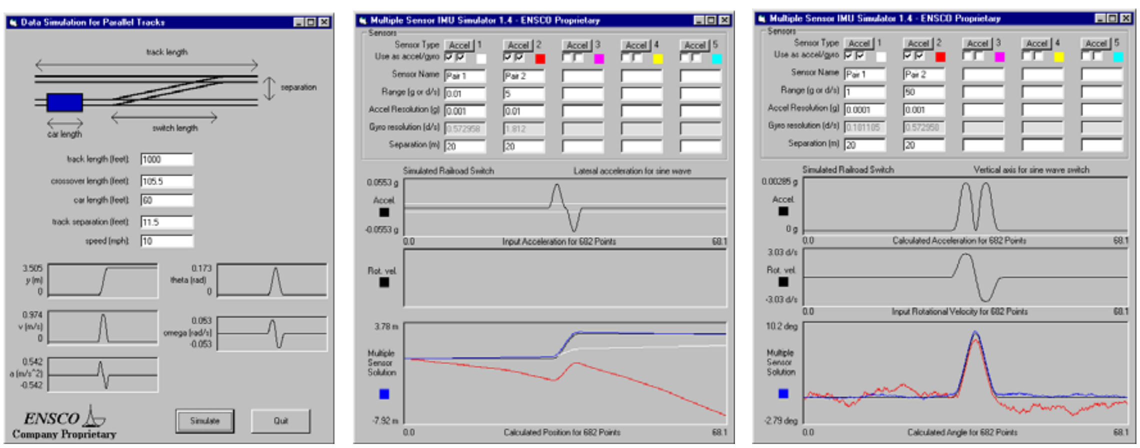


Figure 19. Simulation of sensor data for a locomotive switching between two parallel tracks.

generate acceleration and rotational data that would be produced by accelerometers and gyros located on a locomotive that is switching between two parallel tracks. The data can then be fed into the Multiple Sensor IMS Simulator. The software simulates a single-axis IMS consisting of up to five accelerometers, gyros, or pairs of accelerometers used for rotational sensing. A multiple sensor solution is calculated and displayed, using sensors

with different resolutions and ranges. The simulator operates in two modes: acceleration simulation and rotational simulation. The center panel of Figure 19 shows the data that would be measured for a locomotive switching between two tracks, as measured by two accelerometers with resolutions of 0.01 g and 0.001 g. These are realistic ranges for the Analog Devices accelerometers used in the project, provided that the range of the more sensitive accelerometer is restricted. The simulator shows the accelerations measured by each sensor, as well as the multiple sensor solution, which uses the most accurate of the sensors for each measurement range. The output of the simulated multiple sensor IMS is much more accurate than either of the individual sensors alone. (We plan to extend the software to allow simulation of sensors with different frequency responses.) The third panel shows the simulated angular velocity for a locomotive switching tracks and the corresponding angular velocity measured by pairs of accelerometers.

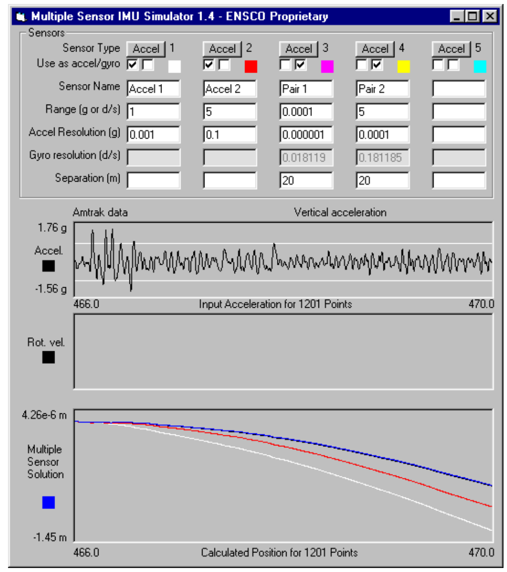


Figure 20. Simulated measurement of rail data with multiple sensors.

We have also performed sensor simulations using recorded railroad accelerometer and gyro data. As an example, Figure 20 shows the Multiple Sensor Workstation using vertical component of acceleration from Amtrak data, Wilmington DL, 11 December 1996. The two lower lines in the bottom panel are the position calculated from individual sensors and the top line is both the "true" result and position calculated from combined sensors.

4.4 LABORATORY TESTING

4.4.1 Laboratory Equipment

For laboratory testing, we purchased an 8-channel, 12-bit data acquisition system and Universal Library interface software from Computer Boards, Inc. We also used existing ENSCO equipment (shown in Figure 21), including nine 901F Active Filter Instruments from Frequency Devices, Inc., a Tektronix 7603 oscilloscope, a Hewlett Packard 3311A function generator, a Hewlett Packard E2378A multimeter, and a Power Designs TW5005T dual power supply. For data recording, we use ENSCO-owned LabTech Notebook software. We have available two Brüel & Kjær 4371 accelerometers for comparison testing.


Figure 21. Laboratory Testing Equipment.

4.4.2 Laboratory Evaluation System

We developed and operated a laboratory evaluation sensor system (Figure 22) that accommodates up to eight sensor channels with 12-bit accuracy. The present configuration includes two ADXL250 two-axis accelerometers

with OP296 dual amplifiers for measuring horizontal acceleration and rotation, an ADXL150 accelerometer with OP196 amplifier for vertical measurements, and three Murata Gyrostar ENV-05D gyros for angular velocity measurements. We have made laboratory measurements of scale factors and noise levels and have also tested the system using external amplification and anti-aliasing low-pass analog filtering. From our test data, we have determined parameters for the multiple sensor computation and filtering algorithms. We have made laboratory measurements with pairs of accelerometers to determine rotational data.

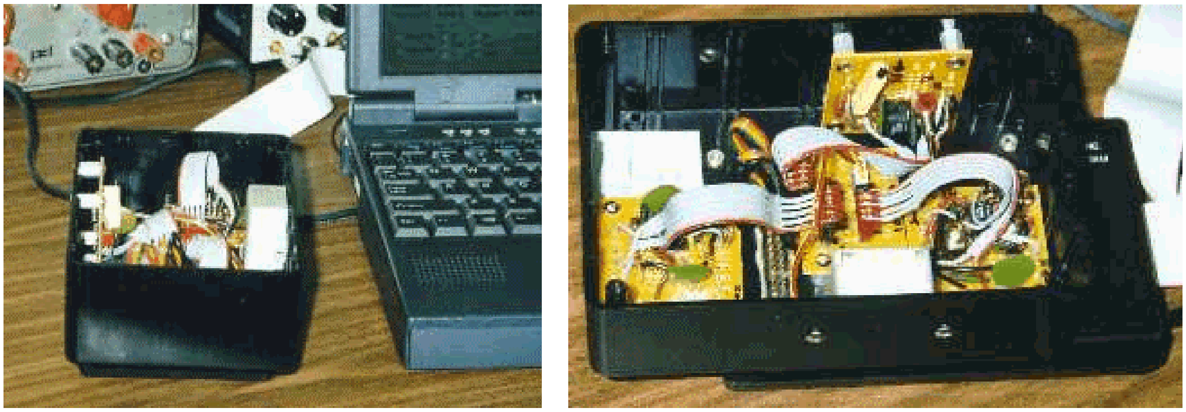


Figure 22. Laboratory Evaluation System.

We developed a software workstation that reads eight channels of data and displays it as raw data, voltage, or acceleration. It also calculates and displays instantaneous and averaged noise levels for raw data, voltage, and acceleration. Velocity and position are calculated from the accelerometer data and displayed. Rotational data can be either obtained from gyros or calculated from pairs of accelerometers. The workstation can combine data from sensors with different ranges. It includes calibration procedures for measuring and recording scale factors of accelerometers. Data can be recorded in files and read back for later analysis. The workstation provides a graphical display of calculated position and angle. The user interface to the workstation is shown in Figure 23.

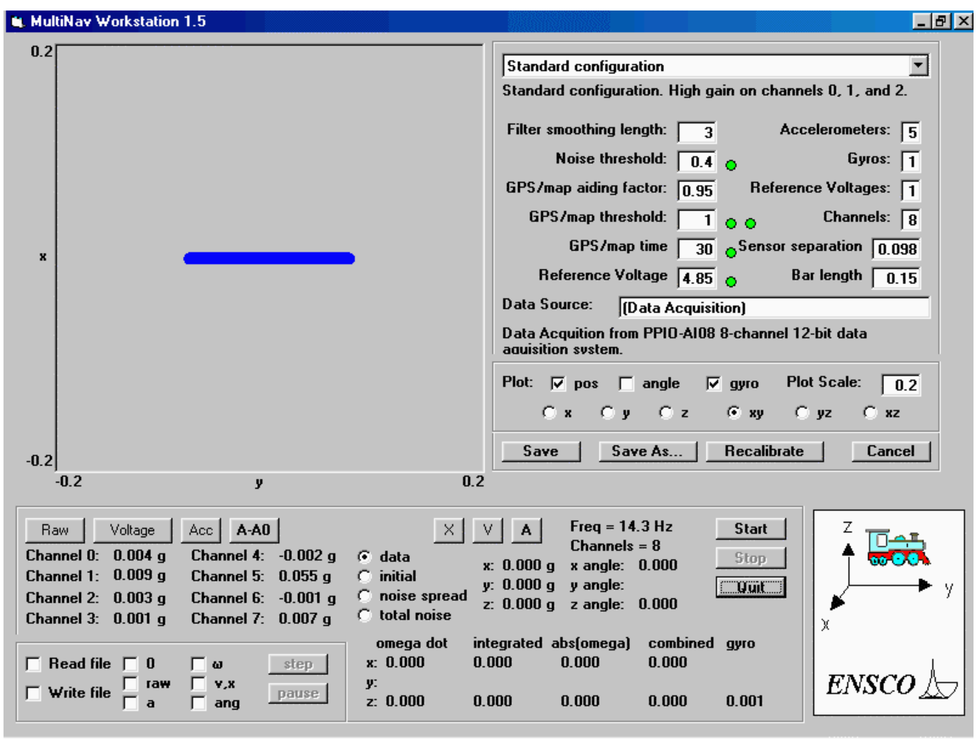


Figure 23. Sensor Workstation for Laboratory Evaluation System.

We have also recorded data from the laboratory evaluation sensor system using LabTech Notebook. An example of recorded data is given in Figure 24, which shows data taken from a motor vehicle that accelerates to 10 miles per hour (y1 panel shows forward acceleration) and changes lanes (x1 panel shows lateral acceleration). The vehicle moves a distance of approximately 10 feet laterally over a travel of approximately 100 feet. The speeds and

distances were chosen to simulate railroad inertial data for a locomotive switching to a parallel track. The figure also shows the vertical acceleration (z1 panel), including oscillation after a dip in the road.

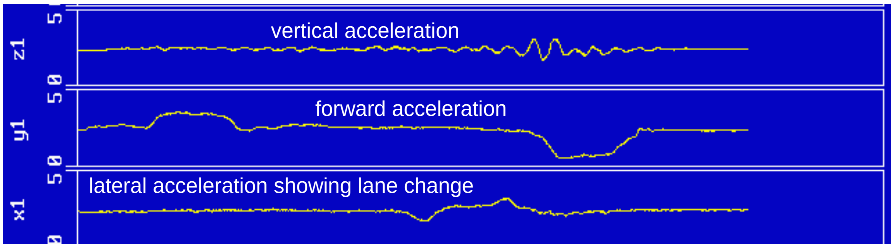


Figure 24. Accelerometer data recorded in a motor vehicle changing lanes (see x1 panel) at 10 miles per hour.

Figure 25 shows measurements made on an elevator in the ENSCO Cocoa Beach office building. The elevator's acceleration was measured as it moved from the second floor to the first floor and back to second. The data indicates that very gentle motion can be detected for distances similar to the distance between tracks.

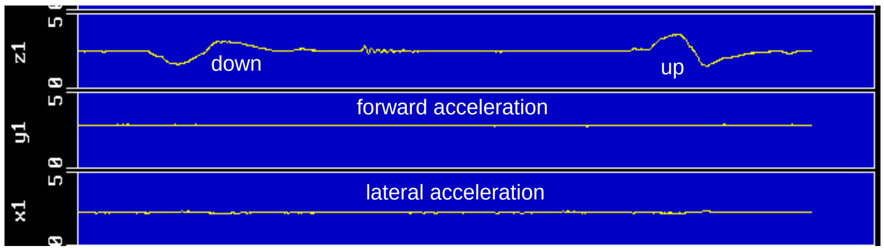


Figure 25. Accelerometer data taken on elevator moving one floor down and back , as another example of detecting motion over distances similar to the separation of parallel tracks.

Based on present laboratory testing, we decided to purchase two additional Murata Gyrostar ENV-05D gyros. The additional gyros allowed us to expand the laboratory evaluation system to provide measurement of three-axis acceleration and three-axis gyro-determined rotation.

We also used the laboratory system to test the four three-axis Analog Devices Accelerometer Evaluation Modules, Model ADXL150EM-3, that were used for field testing. We determined the level of external amplification and filtering required for the field testing.

The laboratory system proved to be extremely useful and has provided much valuable data. It was designed for sensor evaluation, for concept exploration, and for demonstration purposes. However, it has a number of limitations that make it unsuitable for use as a system for field testing. There are timing limitations when the laboratory hardware is used with the MultiNav Sensor Workstation. One is that the data rate is then limited to 15-25 Hz due to the Visual Basic implementation in the Microsoft Windows environment. The system uses the internal computer clock, which has a resolution of approximately 18 Hz. Time intervals measured by the system clock are multiples of 1/18th of a second, and may be zero or as much as twice the actual time. If LabTech Notebook software is used for recording data, then data can be recorded at 100 Hz. However, Labtech Notebook can only be used for data recording and not for real-time processing. There are also a number of limitations due to the data acquisition system, which is a ComputerBoards, Inc. PPIO-08 8-channel 12-bit parallel I/O unit. The system exhibited noise on all channels, even when using no external cabling and with inputs connected directly to ground or power. The noise corrupted the three lower bits of data, reducing the resolution to approximately 9 bits. The system was tested on several computers and power sources with the same results. We also found occasional noise on two of the input channels that may have been due to problems in the sensor hardware. A major limitation is the number of channels. The sensor configuration used for field testing consisted of four three-axis sensors, requiring a minimum of 12 channels. The system also does not have external filtering and amplification required for the accelerometer modules. For these reasons, a completely different system was used for field testing, as discussed in the following section. The laboratory evaluation system was used to record independent data during the field test.

4.5 FIELD TEST

The field test of the MSIMS sensor array was conducted on 3 August 1999 using the Amtrak 10002 High-Speed Track Geometry Car. The system used for field testing is totally independent of the laboratory evaluation system described in the previous section. The system consisted of four three-axis Analog Devices accelerometer evaluation modules, Model ADXL150EM-3 connected to a data acquisition system for amplifying, filtering, and recording the acceleration data.

The modules were arranged in a configuration with modules in two diagonally opposite corners at a low level and at the other two diagonally opposite corners at a high level, as indicated in Figure 26. The modules were positioned inside the car, as close to the corners as possible, as shown in Figure 27. The sensor module locations were chosen to provide as long a baseline as possible for measuring rotation using pairs of accelerometers. In addition to the tested system, signals were recorded from the Track Geometry Measurement System (TGMS) for use as a reference. To provide another independent source of information, the laboratory evaluation system was installed at a central location.

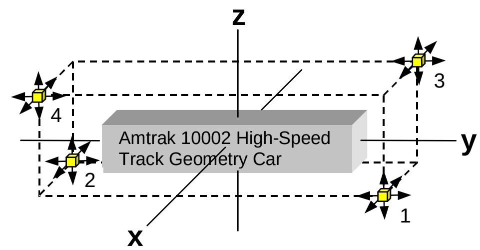


Figure 26. Sensor Configuration for Field Testing.

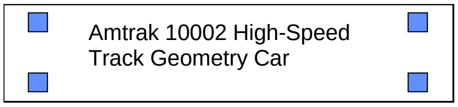


Figure 27. Sensor module locations in top view of 10002 car.

Figure 28. Amtrak 10002 High-Speed Track Geometry Car. Interior view shows ENSCO Data Collection System used for field test.

The ENSCO Field Data Collection System consisted of two National Instruments PCI-MIO-16E-4 data acquisition boards with 24 input lines having 12-bit resolution. It includes two custom made signal conditioning units. Reference data was recorded from five ICS 1% Temperature Compensated 2-g Accelerometers Model 3140, two Systron Donner gyros, GPS, and the ENSCO Automatic Location Detector (ALD).

On 2 August 1999, the day before the test, we installed all equipment on the Amtrak 10002 High-Speed Track Geometry Car, shown in Figure 28. Four sets of three-axis MEMS accelerometers were mounted in the corners of the car, as described in the previous section. The Laboratory Evaluation System was mounted in a central location. Two-axis higher-resolution reference accelerometers were placed at each end of the car for comparison testing. A three-axis higher-resolution reference accelerometer set was co-located with the laboratory evaluation system. It served dual purposes: measurement of car-body rigidity, and comparison testing for the Laboratory Evaluation System.

Testing was conducted from approximately 8:00 a.m. to 4:00 p.m. on 3 August 1999. The 10002 car was on the 8:00 Amtrak Metroliner from Washington to New York and returned on the 1:00 Amtrak Metroliner from New York to Washington. Our only major problem was lack of GPS during the first 45 minutes of the test. (GPS was recorded from the Track Geometry Measurement System, and was not part of the IDEA system.) The external GPS antenna did not function, so a spare antenna was mounted internally and operated for the remainder of the test. Because of a two-hour layover in New York, the total test time was approximately 6 hours.

All data was recorded for later analysis and for testing the navigation and filter software. By using recorded data, the Kalman filter software parameters can be tuned for optimum performance. Such tuning requires multiple runs using identical input data, which would not be possible if the data were processed in real time as collected. All data recording used existing equipment or equipment under development for other ENSCO projects and was provided at no cost to the project. The 10002 car has a specially installed rear window for viewing track conditions. The window was used for photographing track configurations to provide visual information to aid in the analysis of the corresponding recorded sensor data.

4.6 DATA EVALUATION

The main goal of the present data analysis is to determine the ability to extract rotational data from the accelerometer measurements and to determine if switching to a parallel track can be detected. The field test, performed on 3 August 1999, provided approximately six hours of data from the 12 MSIMS accelerometers, 7 reference accelerometers, 2 reference gyros, 2 GPS receivers, the Automatic Location Detector, and the Laboratory Evaluation System's 5 accelerometers and 3 gyros. This substantial quantity of data will be extremely useful for testing the navigation and Kalman filtering software when it becomes fully operational. In the present project, we analyzed a specific set of data to determine the ability to detect switching between parallel tracks.

4.6.1 Switching Between Parallel Tracks

Figure 29. Turnouts viewed from rear window of 10002 Track Geometry Car during field testing.

We identified one particularly good example for analysis that illustrates the process of switching from one track to a parallel track. One reason for choosing the particular event for analysis is that photographs were taken through the rear window of the 10002 car that clearly show the track configuration at the time that the switch occurred. The picture on the left in Figure 29 shows the track while switching and the picture on the right shows the track after switching was complete.

All the data analyzed was be from the MSIMS accelerometers, except for a yaw rate gyro used as a precision reference. The switching event we analyzed, shown in Figure 29, occurred at 10:36:40 a.m. on the route between Philadelphia and Metropark. (This time is indicated as 52600 seconds after midnight UTC (Universal Time Coordinated) on some of the following plots.) The speed of the train was approximately 30 mph, as indicated by the GPS recorded data. GPS data was recorded on both the field system and the laboratory evaluation system. Figure 30 shows a plot of GPS data for the approximate time period. Figure 31 shows data from six of the twelve MEMS accelerometers in the field test. In the body coordinate system used for the test data, x is in the forward direction of motion, y is to the right, and z is down. The figure shows *x*, *y*, and *z* data for one of the three-axis modules in the front of the car and one in the rear. Figure 32 shows higher-precision data from the reference accelerometers and gyros. The lower line of the plot shows the automatic location detector (ALD), which magnetically detects crossing rails at turnouts. The present analysis uses the reference data to provide accurate angular velocity data for comparison to rotation rates calculated from accelerometer measurements.

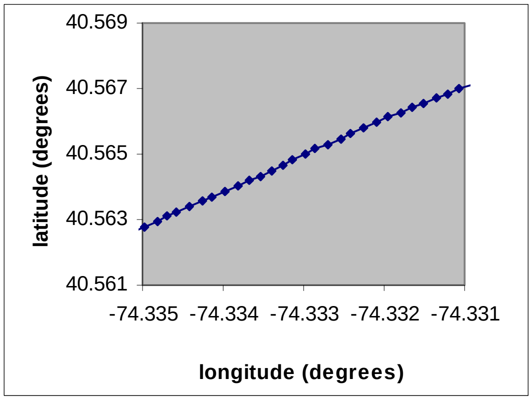


Figure 30. Plot of position determined from GPS. Turnouts cannot be identified from the plot.

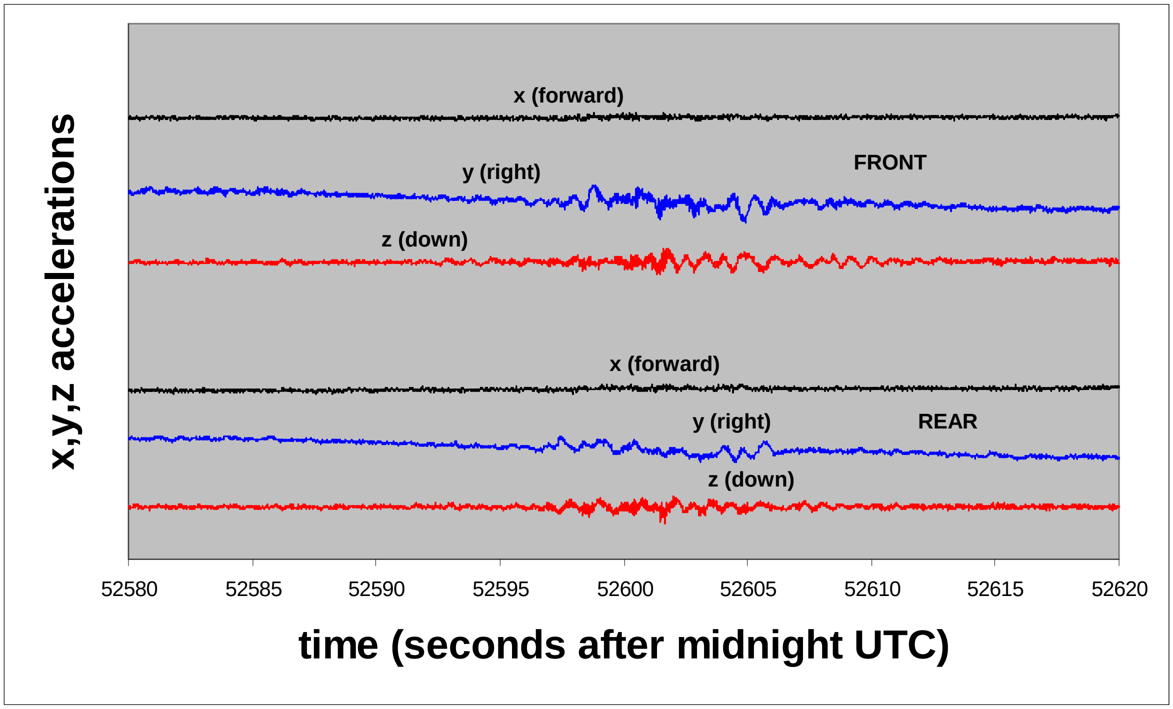


Figure 31. Acceleration data for three-axis modules in front and rear of car while switching to a parallel track (6 of 12 sensors shown). These are the sensors being tested and which provide data to be analyzed for turnout detection.

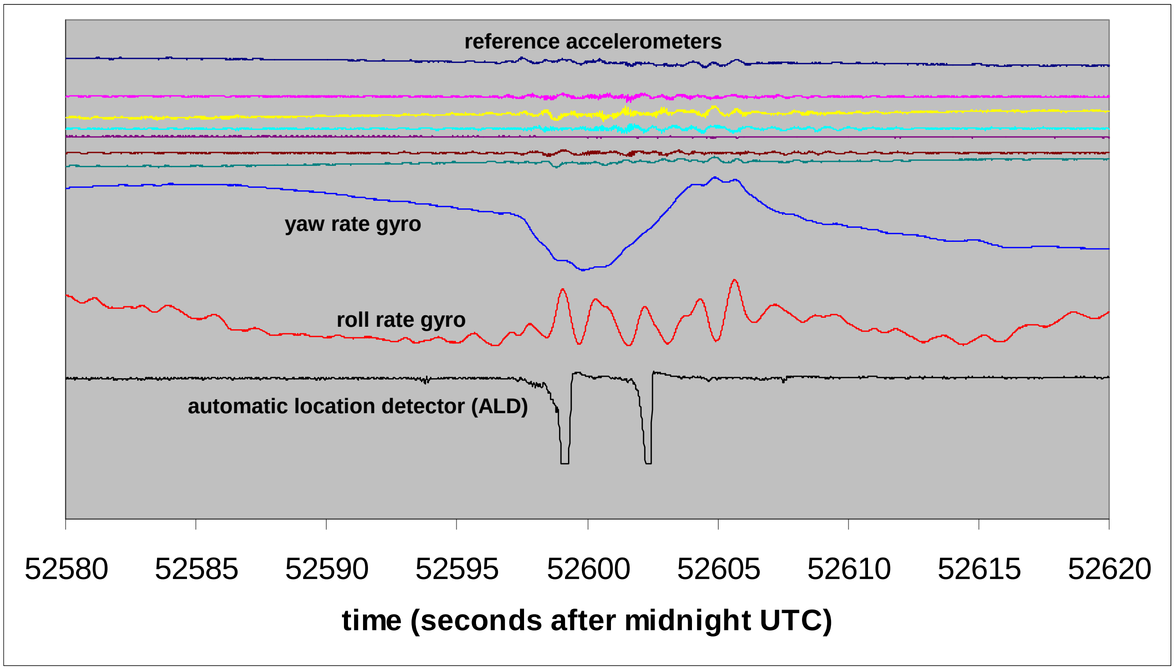


Figure 32. Track Geometry Measurement System reference sensors. From top to bottom: 7 accelerometers, yaw gyro, roll gyro, and automatic location detector (ALD). These are not the sensors being tested, but are provided as reference sensors for comparison.

The following analysis shows how the data in Figure 31 can be used to detect turnouts. The method uses accelerometer data to calculate rotational data of the type usually obtained from gyros. The difference in lateral acceleration between the two ends of the rail car is used to compute the angular acceleration about a vertical axis, which is then integrated to obtain the angular velocity. A detailed discussion of this method is given in Section 3.3.1. The rotational signature (angular velocity as a function of time) of a rail car or locomotive turning onto a turnout was simulated in Section 4.2 (see Figure 19). This analysis will determine whether the signature can be extracted from the field-test data.

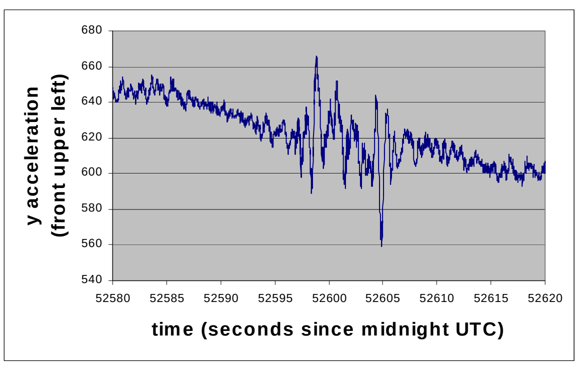


Figure 33. Data from single accelerometer.

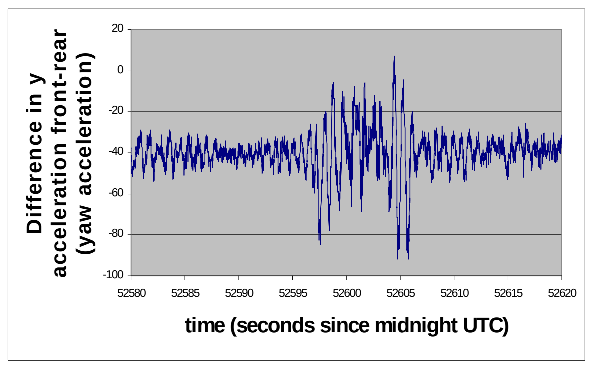


Figure 34. Yaw angular acceleration calculated from accelerometers.

The first step is to calculate the angular velocity from the lateral accelerometer data. Data from a single lateral MEMS accelerometer (y direction in body coordinates) is shown in Figure 33. (The units on the y axis are raw data, as recorded directly by LabTech Notebook.) As discussed earlier, the angular acceleration about the vertical axis (yaw acceleration) is proportional to the difference between the average of the front lateral accelerometers and the rear lateral accelerometers. This quantity is shown in Figure 34. The usual output from a gyro is angular velocity, rather than angular acceleration. The angular velocity is obtained as the integral of the angular acceleration. This integrated quantity is shown in Figure 35. The result compares favorably with the corresponding data from the Systron Donner yaw rate gyro, shown in Figure 36.

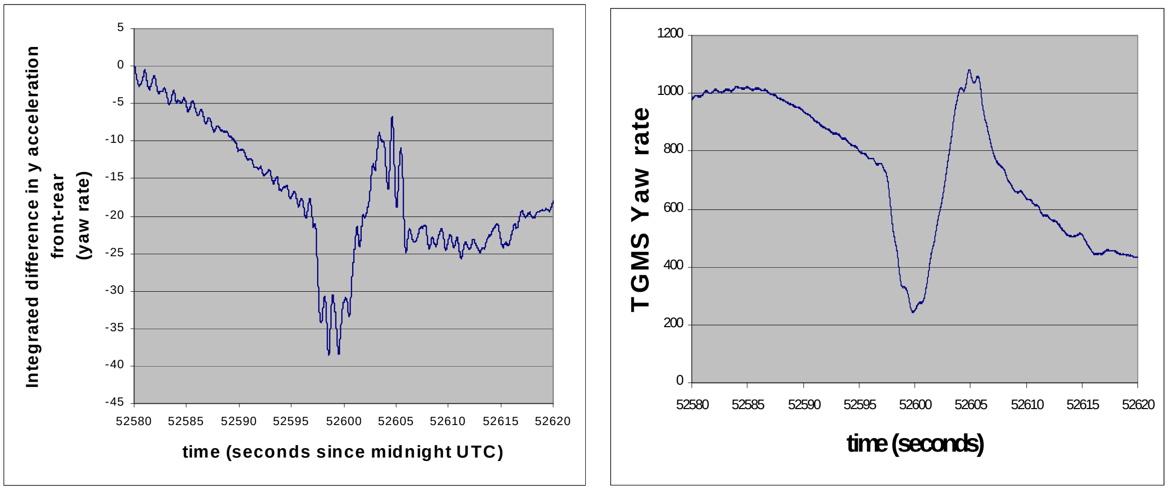


Figure 35. Calculation of yaw rate (angular velocity about the vertical axis) from accelerometer data. The plot on the left is calculated from accelerometers. For comparison, the plot on the right is the yaw rate from the Systron Donner precision reference gyro.

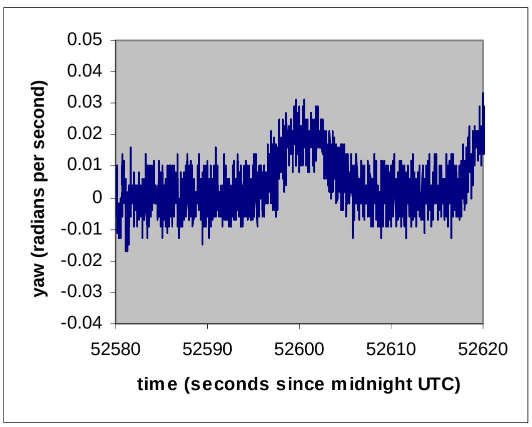


Figure 36. Murata gyro data for rotation about vertical axis plainly shows rotation at turnout, but does not provide the accuracy seen in the data from accelerometer pairs or the reference gyro.

Another comparison can be made to the yaw rate measured by the Murata gyros from the laboratory evaluation system. For the same time period, the data is shown in Figure 36. The data is unfiltered and, hence, has greater noise than either the Systron Donner gyro or the data calculated from accelerometer data. However, the important thing to note is that the gyro only indicates a rotation in one direction, which would indicate a permanent change in direction, not a transfer to a parallel track. The Murata gyro is relatively expensive in comparison to a pair of MEMS accelerometers, yet does not perform as well as either the accelerometers or the Systron Donner gyro. If this analysis is typical, then it appears that using pairs of accelerometers for calculating angular velocity can be superior to the use of inexpensive gyros.

The above calculation shows that conventional gyro output can be determined from pairs of accelerometers. As another test, the reverse calculation can also be performed: The angular acceleration can be calculated as the time derivative of gyro angular velocity and compared to the results calculated directly from accelerometers. In Figure 37, the angular acceleration from accelerometers is compared with the angular acceleration calculated as the time derivative of gyro data.

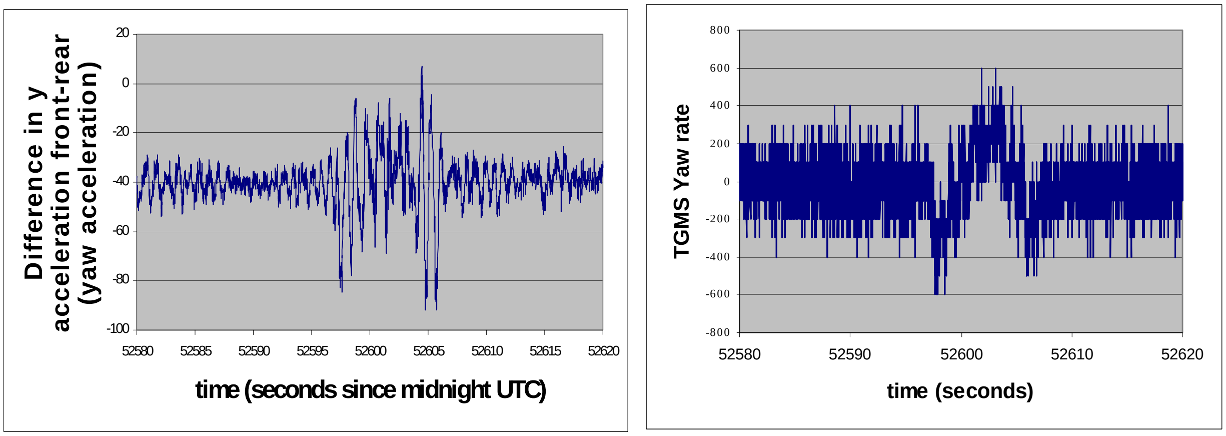


Figure 37. Yaw acceleration calculated from accelerometers. The plot on the left shows the angular acceleration calculated from accelerometer data. The plot on the right is the time derivative of gyro data. The plots show too much noise for a visual comparison without smoothing.

In order to compare the two results visually, it is necessary to smooth the data. (For inertial applications, the data would be integrated and would not require smoothing.) The plots in Figure 38 are the same as in Figure 37, but with equal amounts of smoothing.

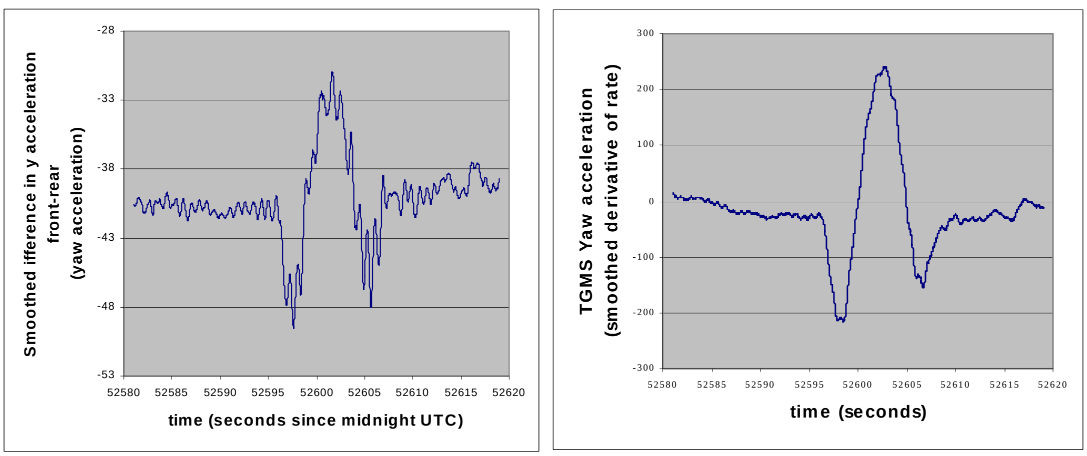


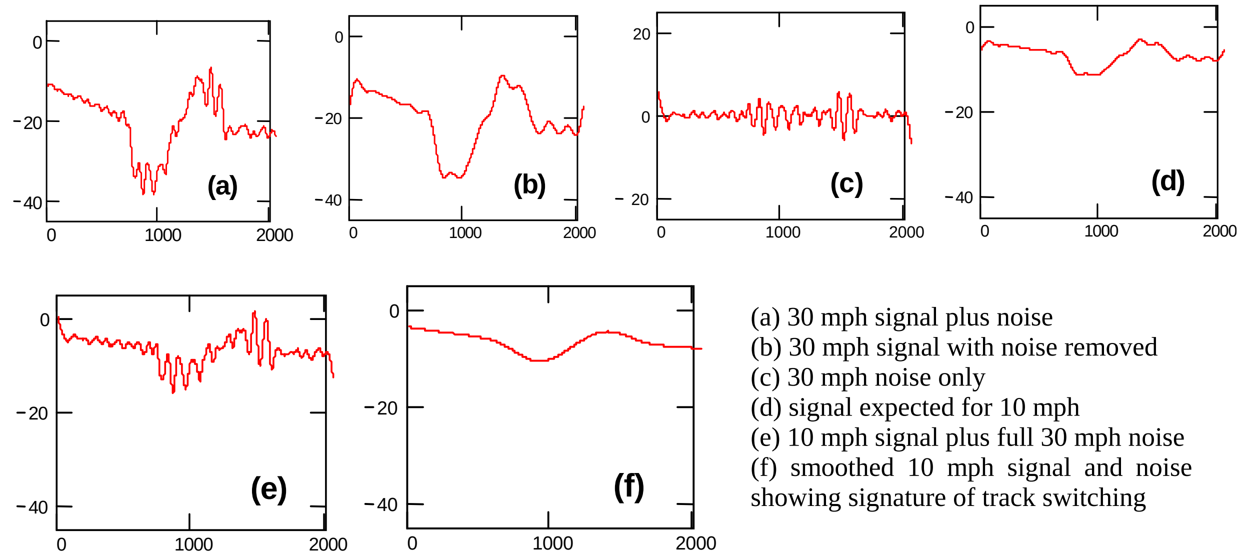
Figure 38. Left: smoothed yaw acceleration calculated from difference of average front and rear lateral accelerations. Right: smoothed derivative of yaw rate from Systron Donner reference gyro from Track Geometry Measurement System.

It should be obvious that whether angular velocity or angular acceleration is being used, there is a clear signature for switching to a parallel track. (In practice, we plan to integrate the angular acceleration as in Figure 35, rather than smoothing.) The angular velocity signature is very similar to the data simulated at the start of the project, and shown in the first panel of Figure 19.

4.6.2 Extension of Analysis to Lower Speeds

A goal of this project was to show that the field system could detect switching to a parallel track at 10 mph. During the field test, we did not identify any cases of switching tracks at or about 10 mph. However, from additional analysis of the 30-mph data, it is straightforward to determine whether 10 mph switching is detectable. We first remove the high-frequency noise from the accelerometer data in Figure 35 by using a Fourier transform and removing the higher frequencies. The original and filtered signals are shown in Figure 39 (a) and (b) and the extracted noise alone is shown in (c). (The data interval was reduced from 4001 points to 2048 points to allow the use of a fast Fourier transform.) We next reduced the 30 mph signal by a factor of three to estimate the signal (with no noise) expected at 10 mph, as seen in Figure 39 (d). As a worst-case scenario, we assume that the noise at 10 mph is just as high as it was at 30 mph, so we add in the full noise to the 10 mph signal to obtain the worst expected 10 mph signal plus noise, Figure 39 (e). By smoothing the estimated 10 mph signal plus noise, we see in (f) that the signature of a switch to a parallel track is plainly evident. This analysis of this specific data set clearly demonstrates

that a turnout should be detectable at 10 mph. We did not analyze other data, such as switching to a more distant parallel track.



(a) 30 mph signal plus noise
(b) 30 mph signal with noise removed
(c) 30 mph noise only
(d) signal expected for 10 mph
(e) 10 mph signal plus full 30 mph noise
(f) smoothed 10 mph signal and noise showing signature of track switching

Figure 39. Demonstration that track switching should be detectable at 10 mph.

The recently announced Analog Devices ADXL105 MEMS accelerometers have approximately 5 times the resolution of the ADXL150 sensors used for the field test. The ADXL105 has a range that can be set to 1 g, while the sensor modules used for the field test were preset to have a 10-g range. Using the improved sensors, we may thus be able detect switching at 1-2 mph, and even slower if there is a significant decrease in acceleration noise at low speeds. We plan to use ADXL105 sensors for our future MSIMS product application.

4.6.3 Overall Accuracy of Future Inertial Navigation Systems Based on Present Analysis

We plan for the product developed from the present effort to include wheel tachometer data as an additional sensor input. Wheel tachometer signals are available on all locomotives and can be used as a measure of distance and speed when DGPS is unavailable. A precision tachometer of the type used in the Track Geometry Measurement System on an unpowered axle is typically accurate to 1 percent. Locomotive tachometers have decreased accuracy due to slipping when starting or on grades. A certain amount of slipping is unavoidable, and even intentional. Locomotives with creep control permit slipping to increase acceleration. For example, the GM Class 59 diesel-electric locomotive has creep control allowing the wheels to turn 5% to 15% faster than actually required by the train speed (*12*). The Q-TRAC 1000 from Q-Tron allows the locomotive's wheels to creep at 1-2 mph above rail speed (*13*).

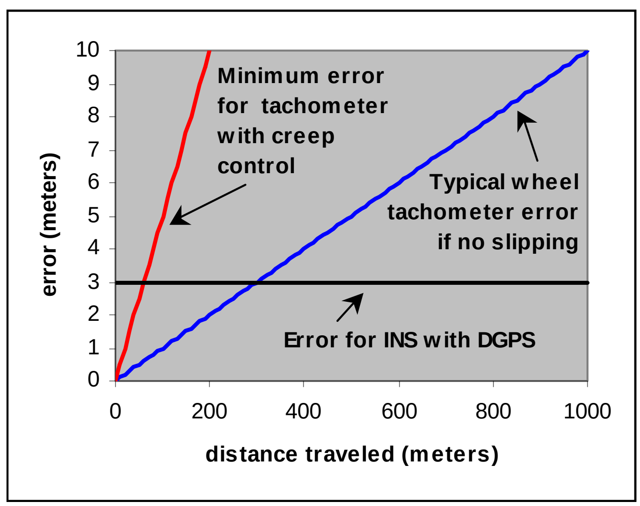


Figure 40. Error for wheel tachometer alone, compared to inertial navigation system.

When used as input to an inertial navigation system, the wheel tachometer provides speed information and can be automatically aligned by the Kalman filter (using DGPS and inertial data) to provide unbiased results for periods of DGPS outages. Short periods of slipping can be detected and compensated by the use of inertial sensor data, and the wheel tachometer data can place an upper bound on the along-track position errors. It should be possible to determine location to within the accuracy of the DGPS position, with a drift of within 1 percent of distance traveled during periods when DGPS is not available. Figure 40 shows the accuracy of such a DGPS-based INS compared to the accuracy of a wheel tachometer with and

without slipping. The line for creep control assumes 5 percent slipping. From the figure, it is clear that the INS will be much more accurate than the wheel tachometer used alone.

From the analysis of field test data in Section 4.6.1, and taking the addition of wheel tachometer data into consideration, the inertial navigation system product based on this project should have accuracy within DGPS accuracy when DGPS is available, should drift off at no more than 1 percent when DGPS is not available, and should be able to detect switching to a parallel track at speeds below 10 mph. Because the Kalman filter used in a navigation system automatically corrects slowly varying biases, such as wheel tachometer errors, the initial drift when DGPS is lost should be significantly less than 1 percent. However, the improvement due to Kalman filtering cannot be estimated until after we have completed checkout and optimization of the filtering and navigation software. In addition to the location accuracy, the INS must be able to detect switching to a parallel track at a turnout. As explained in Section 4.6.1, switching may be detectable at as low as 1-2 mph with the use of the recently announced ADXL105 MEMS accelerometers.

4.7 PRESENTATIONS AND COMMUNICATION

4.7.1 Panel of Advisors

We held panel meetings on 17 March 1999 and 3 October 1999 with a panel of user representatives, technical experts, and system integrators. The panel included representatives from the railroad industry and two personnel with interests in MEMS sensors and navigation from Eglin Air Force Base. The first meeting reviewed system requirements, architecture, and approach. The second meeting reviewed project progress and field test results. Both meetings were held at the Radisson Riverwalk Hotel in Jacksonville, FL. The following table lists the panel members:

Name	Company or Agency	Location	Position	Attendance
Chuck Taylor	NRC/TRB	Washington, DC	Program Manager	Panel Meetings 1 and 2
Denny Lengyel	ARINC	Annapolis, MD	Technical Advisor	Panel Meetings 1 and 2
1Lt Laura Kelly	USAF	Eglin AFB, FL	Panel Member	Panel Meeting 1
Capt Nathan Barnes	USAF	Eglin AFB, FL	Panel Member	Panel Meeting 2
Ron Lindsey	Communication Architecture	Jacksonville, FL	Panel Member	Panel Meeting 1
Bill Matheson	GE-Harris	Melbourne, FL	Panel Member	Panel Meeting 1
Bill Petit	Safetran	Rochester, NY	Panel Member	Panel Meeting 2
Gerhard Thelen	Norfolk Southern	Philadelphia, PA	Panel Member	Unable to attend

Table 2. Expert Review Panel.

Both meetings were attended by ENSCO personnel Manuel Perez, Greg Taylor, Brian Mee, and Fred Riewe. The first meeting was also attended by consultant Harry Gaines. In addition to the panel meeting, a teleconference was held on 30 March 1999 to discuss the Joint PTC System Specification. Participants were Denny Lengyel, Chuck Taylor, Brian Mee, Manuel Perez, and Fred Riewe. The discussion focused on PTC core objects and the development of a location object during the second phase of the project.

4.7.2 Oversight Committee Presentation

We prepared and presented a project description and progress report for the NAS/TRB High Speed Rail IDEA Program Oversight Committee. The presentation was given at the National Research Council Building in Washington, DC on 17 November 1998.

4.7.3 Seminars on Kalman Filtering, Navigation, and Digital Signal Processing

During Stage 2, we successfully leveraged our IDEA funding to provide four days of classes (five hours each day) covering the technical areas essential to our contract work involving navigation algorithms and Kalman filtering. Classes were presented by our IDEA contract consultant, Harry Gaines. By using ENSCO overhead funding and by scheduling half of the class time after normal working hours, we were able cover all four days for the participants and all but one day for the class instructor without charging the IDEA contract. The only charge to

the IDEA contract was one 8-hour day of consulting time. From January through October 1999 we held a series of Digital Signal Processing classes that relate directly to our contract work. The weekly classes were held during lunch hours, used video taped lectures from the ENSCO Library, and did not require funding from the IDEA contract.

4.7.4 Documentation

The following documents were prepared as part of the project:

- *System Specification for the Multiple Sensor Inertial Measurement System for Locomotive Navigation,*
- *Algorithm and Performance Requirements for the Multiple Sensor Inertial Measurement System for Locomotive Navigation,*
- *Field Test Plan for the Multiple Sensor Inertial Measurement System for Locomotive Navigation,*
- Monthly progress reports,
- *Stage 1 Report* and *Stage 2 Report*, and
- *Low-Cost Multiple Sensor Inertial Measurement System for Locomotive Navigation: IDEA Program Final Report for the Period July 1998 Through October 1999* (this document).

Also, two internal ENSCO documents were prepared to document the filter, navigation, and sensor algorithms.

5. PLANS FOR IMPLEMENTATION

5.1 DESIGN OF COMMERCIAL SYSTEM

The basic assumption made for commercializing the MSIMS is that it will become a component of an overall PTC system. This assumption follows the design philosophy of the Eastern Railroads PTC On Board Platform (OBP). This MSIMS component could be offered to major PTC equipment manufacturers for integration into their complete PTC systems, or to the railroads as a module or object suitable for specification in their PTC equipment buys. The MSIMS may have another niche as a low-cost backup or additional navigation system to increase the availability of a locomotive PTC system by providing a check on the primary navigation system solution and allowing the PTC system to fail to a safe mode if the primary navigation system becomes inoperative.

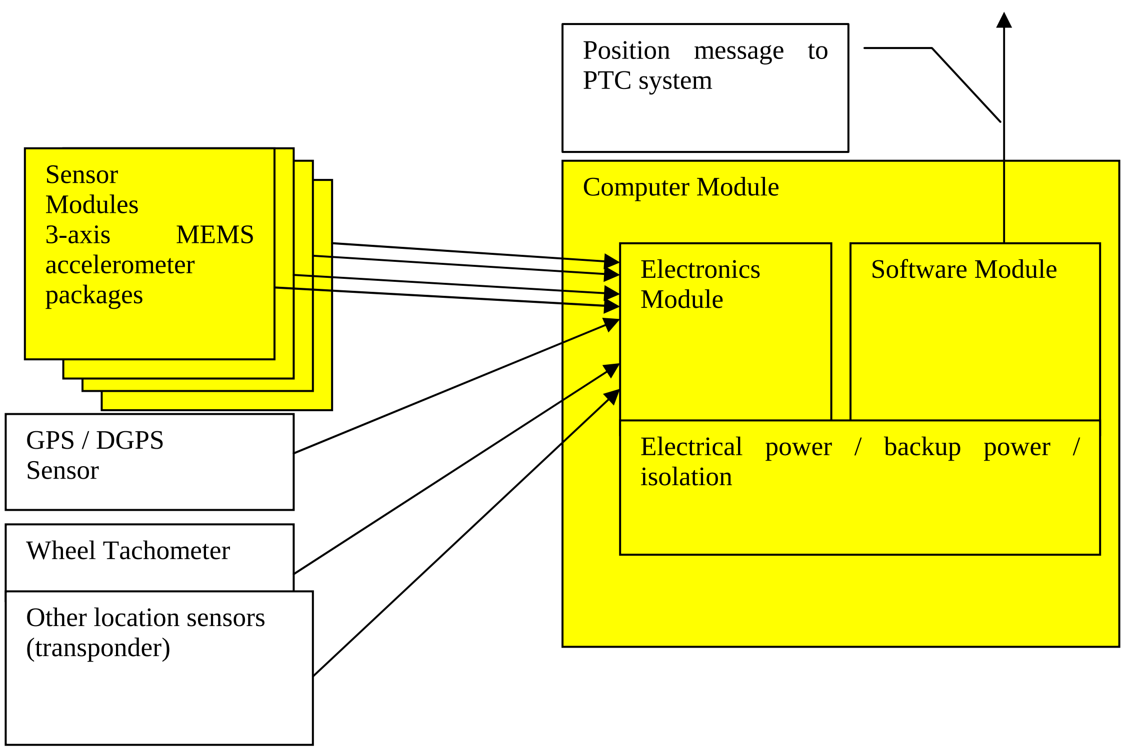


Figure 41. MSIMS Production system block diagram.

The design of the MSIMS for commercial production and implementation will concentrate on the individual modules of the system as shown in Figure 41. This architecture is flexible and can be implemented on a variety of railroad vehicles. By its nature, the MSIMS is a distributed system. The accelerometers will be mounted in corners of the vehicle and the remainder of the modules can be placed in proximity to the rest of the PTC equipment that will probably be located in or near the cab. Interfaces from the MSIMS to other systems on the locomotive include the bus connection to the OBC, direct connection to a GPS/DGPS receiver, direct connection or bus connection to a wheel tachometer, and connections to any other location determination sensors installed such as transponders.

The production of the MSIMS will be eased by the extensive use of commercial off the shelf (COTS) components. The market for MEMS accelerometers continues to grow with automotive and other applications driving the prices down and performance up.

The production MSIMS will consist mostly of COTS equipment with standard modules containing electronics, computer, and interfaces. The cable lengths required will vary with the type of installation, such as locomotive or hi-rail truck, and with specific models of locomotives, different manufacturer, etc. Standard installations will need to be engineered for each vehicle so that the accelerometer ranges and key dimensions such as the X,Y,Z location of the sensor modules can be controlled to match calibration and initialization data files for the MSIMS software. Installation of MSIMS sensor modules will also require mounting brackets and other hardware items. The MSIMS will be packaged as an installation kit including the sensor modules, computer cards or module, connectors, brackets, cables, and other equipment. The MSIMS can then be installed either during locomotive manufacture, or as a retrofit installation during a normal locomotive maintenance operation. The MSIMS will have built-in calibration and test routines to aid installation, checkout, and calibration. The location of the sensors is discussed earlier in this report and is shown in Figure 42.

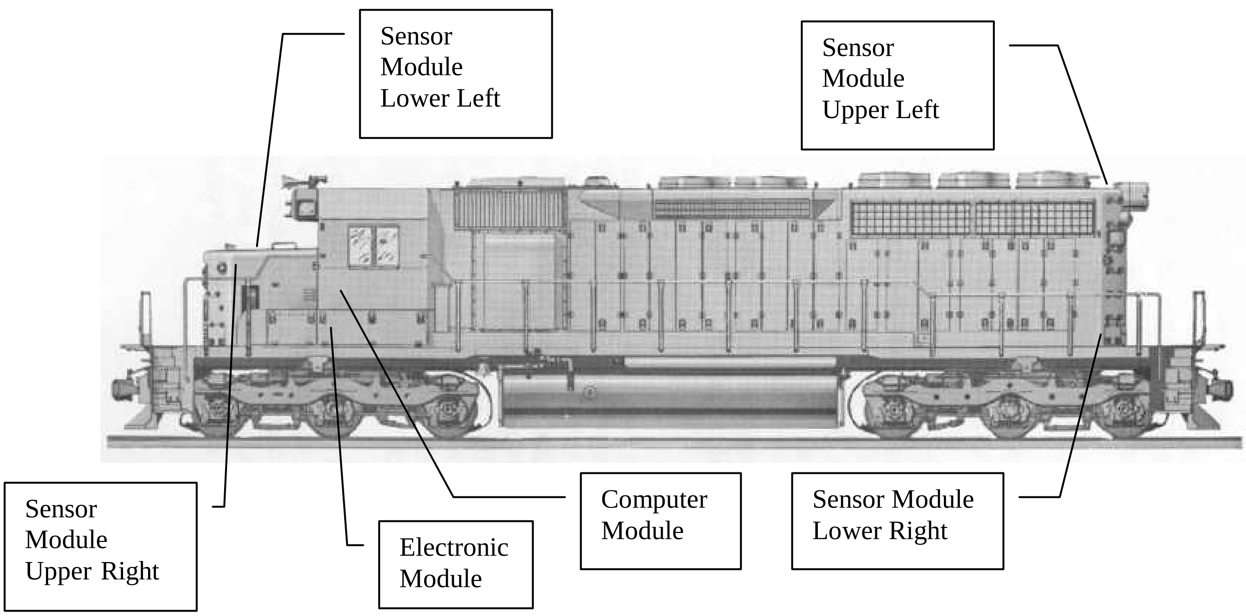


Figure 42. MSIMS Module Locations Production Installation.

We plan to develop accurate calibration procedures for the sensor alignment. Calibrating the accelerometers of a cluster of inertial sensors may be carried out by collecting their data in several static orientations and fitting it to an error model. Three biases, three scale factor errors and three mutual misalignments (non-orthogonality angles) can be determined from data from twelve orientations: each of the three input axes up and down, and each of the three input axis bisectors up and down. A simple, stable holding fixture suffices because precise orientations are unnecessary. The accelerometer output itself establishes them. Of course, more orientations and longer data collection periods improve the calibration. Designing the procedure to a desired accuracy is supported by the fact that the covariance matrix of the error of the fit is simply the inverse matrix of the normal equation scaled by the variance of the data errors.

The sensors will first be calibrated in a laboratory setting. To transfer the sensors to the locomotive, we have two methods that will be evaluated and a choice made during development. One is to use mounting brackets that allow the sensors to be tilted through angles to perform an alignment procedure similar to the laboratory calibration. The second method is to use fixed mounting brackets with internal alignment adjustments to duplicate the laboratory alignment. Horizontal alignment is simple because the sensors are sensitive to gravitational acceleration. Alignment of the third axis can be performed in several ways, the simplest of which is to have the locomotive on a grade and align using the lateral accelerometers.

5.1.1 Sensors

There are several options for implementation of the sensors needed for the MSIMS. The field testing was performed using COTS three-axis accelerometer packages. A production version could be made using these same units. However, due to the different ranges of acceleration expected in the lateral, vertical, and longitudinal axes on trains, a custom version of the three-axis module could be specified with different sensitivities on each axis. This might be accomplished using commercial sensors with different gains set by strapping or resistor selection, or could require a production run with different types of MEMS sensors on each axis. Currently, the Analog Devices ADXL105 is the accelerometer most suitable for use as the most sensitive sensor. The present project has shown the advantages of using multiple accelerometers with different sensitivity ranges on the same axis. In production, this could be deployed by using multiple MEMS accelerometers on the axes of interest, either by custom made modules or by using more than one set of MEMS accelerometers at a given location. A wide-range sensor and a high-resolution sensor can be used in combination to provide a wide range of measurement, while not sacrificing accuracy at typical accelerations encountered by the application. Because the range of some MEMS sensors can be electrically reconfigured, an array of similar devices can be tuned to provide the optimum overall accuracy.

5.1.2 Computer

The proof of concept design MSIMS, developed during the current project, is not a real-time system. The production version will need a computer or processor to handle the I/O, Kalman filtering, message processing, built-in test capability, and other functions. Depending on the actual installation and the outcome of the various PTC projects, there are several options for implementing the computer module of the MSIMS.

The least development risk is associated with using a separate single-board rugged computer with an interface provided to the main On Board Computer (OBC) of the installed PTC system. These computers are available commercially in ruggedized form for standard buses including STD-32, compact PCI, PC-104 and others. In this design, the MSIMS computer would be a stand-alone unit with its own power supply and would interface with the MSIMS sensors, GPS/DGPS, wheel tachometer, any other locomotive sensors required, and the PTC OBC.

A more compact and less costly approach would be to implement the MSIMS computer as a board or boards located within the OBC card cage. In this design, the external interfaces to GPS, wheel tachometer and other PTC-related sensors would be via the OBC bus. Direct interfaces to the MSIMS accelerometers from the MSIMS Analog-to-Digital (A/D) board would be needed. This design would be less costly to produce, but would require additional design, integration, and testing with each type of PTC OBC used in the industry.

5.1.3 Software

The Kalman filter developed in this project was written in Fortran and designed for post-test data processing. In production, these algorithms will need to be implemented in a real-time environment. There are several options, depending on the anticipated number of MSIMSs that will be produced and the tradeoff between development costs and production costs. The simplest method of converting the MSIMS to a real-time system would be to re-host the code in C running under a real-time operating system such as QNX 4.25. Another possibility would be to implement the code as a C language object in LabView. Either of these could be the approach for the next phase of development.

The next step towards quantity production would be to re-host the signal processing, Kalman filtering, and communications functions on an OEM processor board, either as a stand-alone box with interfaces to the OBC, or as a card within the OBC card cage. This approach has advantages in that the specific MSIMS program can be contained in a programmable read only memory (PROM) chip which loads the program at each power up. In this configuration, there is no risk of data or program corruption due to operator error or operating system hangs etc.

Specific PROMs could be programmed for each MSIMS installation and configuration control would be eased by controlling the PROM as a piece of hardware rather than controlling and verifying software loads before each trip.

A more complicated approach, but potentially more cost effective, is to re-host the signal processing, Kalman filtering, and communications functions in Field Programmable Gate Arrays (FPGAs). As with the OEM processor board, the MSIMS program can be stored in a PROM chip that loads the program at each power up. If large quantities of MSIMS installations were anticipated, the FPGA programs could be used to program application specific integrated circuit (ASIC) chips. The ASIC would then probably be installed with signal processing electronics on a single card that could then either be installed as a stand-alone box with interface to the OBC, or as a card within the PTC OBC card cage. The ASICs could be produced at very low cost. However, there is a substantial cost associated with developing the mask for the initial ASIC production.

5.1.4 Electronics

The electronics module will consist of the components necessary for isolation, signal conditioning, analog-to-digital conversion, gain and offset setting, and suitable interfaces. One of the primary functions of the electronics module will be to protect the system from the ElectroMagnetic Interference (EMI) environment encountered on a locomotive. Proper signal grounding and low pass filtering will be used to avoid introducing high frequency noise into the Kalman filter. The low pass filters will also act as anti-aliasing filters for the acceleration data. The gain and offset for each accelerometer will be adjustable in the electronics module. Stabilized electric power for each MEMS accelerometer will be sent from the electronics module to the sensor modules along the signal cables. The external interfaces to the MSIMS will be located at the electronics module. These will include a pulse interface to the wheel tachometer, a serial interface to the GPS/DGPS receiver, and any other external interfaces used.

5.1.5 Packaging

5.1.5.1 Sensor Modules

As noted above, the MSIMS will be packaged into two or three enclosures connected by cables. The sensor modules will be rugged environmentally sealed enclosures containing the MEMS accelerometer chips. An example is shown in Figure 43.

Figure 43. MEMS Accelerometer Module Enclosure.

Figure 44. Example of electronics module enclosure.

5.1.5.2 Electronics Module

The signal conditioning electronics components will be installed in another environmentally sealed enclosure suitable for mounting anywhere in the locomotive. An example of this type of enclosure is shown in Figure 44.

The four sensor modules in each installation will interface with the electronics module by multi-pair cables and standard rugged connectors. The output of the electronics module will be a conditioned analog signal for each sensor sent to the computer module for digitization and processing.

5.1.5.3 Computer Module

The computer module will contain the analog-to-digital converter, processor card or signal board computer card, and its power supply. Initially this will probably be implemented as a stand-alone box similar to that shown in Figure 45. The computer module could also consist of an analog to digital converter and a processor card in the overall OBC card cage if desired.

Figure 45. Computer stand-alone module enclosure.

5.1.5.4 Installation and Calibration of Sensors in the Locomotive

We plan to extend the existing Kalman filter to include additional methods for correction and calibration of sensors. Our approach is to adjust the individual sensor compensation parameters (thermally sensitive bias scale factor and alignment corrections) so that the resulting signal is compatible with the composite filter solution. Fault detection will be accomplished by the same type of internal comparisons.

5.1.6 Costs

We have calculated material and labor costs for each of the implementation options for the MSIMS product. We found the following totals, which include hardware, software, and assembly:

Implementation	Type	Cost
Stand-Alone Computer	prototype	$8500
Installation in OBC	prototype	$8000
FPGA Implementation	production	$6500
ASIC Implementation	production	$2500
Production OEM card	production	$2500

Table 3. Estimated Costs.

The first two options show the cost of implementing prototype units. The FGPA implementation does not include the development costs for FPGA programming. The ASIC and OEM costs are for production units. The original cost goal of $1000 does not appear achievable. However, the MSIMS does represent a unit cost reduction of the order of tens of thousands of dollars in comparison to conventional inertial systems. This is a significant saving for the railroads in cost to equip their locomotives.

5.1.7 Testing and Quality Assurance

Laboratory tests, simulations, and a locomotive field test are planned to optimize and finalize the application design. The product will use the location, type, and orientation of sensors described earlier in this report. Once the product application has been developed and tested on a locomotive, the next step will be a long-term field trial on an actual locomotive in service. This would allow concerns such as reliability, EMI, long-term stability, and others to be addressed. Following a successful demonstration, the technology would be offered to locomotive manufacturers, communication-based train control system integrators, and other interested industries for production.

5.2 COMMERCIALIZATION

ENSCO, Inc. has its roots in signal processing and digital filter design and remains a leader in this arena, especially in the fields of space-program applications, geophysics, and railroad track geometry. Commercialization of this effort will enable us to expand our signal processing and filter design expertise to include inertial guidance. The project ties directly to ENSCO's work for Eglin Air Force Base on anti-jam GPS antennas. ENSCO plans to combine its IMS and GPS efforts in order to develop integrated GPS Inertial Navigation Systems. The project will also open commercial markets to ENSCO as part of a team to produce low-cost MSIMSs.

There are many military applications, including application to munitions such as smart bombs, tactical missiles, and guided artillery, as well as military applications for ships, ground vehicles, and aircraft, including unmanned targets, drones, and undersea vehicles. Besides the immediate objective of producing commercial MSIMSs, ENSCO's goal for military applications is to integrate the MSIMS with the anti-jam GPS receivers that were developed by ENSCO under a Phase II SBIR. The end product will be a low-cost integrated anti-jam GPS Inertial Navigational System.

In the commercial sector, the immediate application of the MSIMS is for the ongoing ENSCO projects in railroad track geometry measurement, ride-quality measurements, and subsystems for positive train control. ENSCO presently operates railroad vehicles instrumented with inertial systems and GPS receivers for the FRA. We have evaluated inexpensive sensors for use in these applications. A remote ride quality measurement system, developed by ENSCO under FRA BAA and SBIR funding, using MEMS sensors has been chosen by Amtrak to monitor safety of the new Acela high speed train. This unit is being commercially marketed to railroads, commuter lines, and transit properties for passenger safety and quality assurance. We have a present and future need for low-cost IMSs, both alone and coupled to GPS. The positive train control subsystems we are developing will have widespread use in the railroad industry.

There are many other commercial markets for low-cost IMSs, both commercial and reduced accuracy. These include many new applications that have only become feasible because of the availability of inexpensive GPS systems that can be integrated with IMSs. The advent of inexpensive GPS and DGPS systems has spurred the development of many commercial applications that require IMSs of both tactical grade and lower accuracy. The IMS is integrated with GPS for improved accuracy or for periods when GPS is blocked (as in tunnels) or otherwise unavailable. These applications include automotive sensing, vehicle guidance and tracking, surveying, geodesy, railroad track geometry measurement, and aircraft navigation. As IMS prices continue to decline, there are promising innovative future applications including guidance for robotics, guided farm machinery, and even autonomous lawn mowers.

The product we plan to develop based on the present effort will reduce costs without sacrificing accuracy by using multiple low-cost MEMS accelerometers to replace more expensive single accelerometers and gyros. A locomotive provides an ideal environment for using a long baseline between pairs of accelerometers to achieve accurate angular inertial measurements. The product will have a small size, due to the use of MEMS accelerometers. Unlike general purpose inertial systems, it will be geared to locomotive applications by optimizing the measurement of forward location and lateral motion and taking into consideration the one-dimensional constraint of railroad track. It will take advantage of all sensor information unique to railroads, including wheel tachometer, map information, transponders, and turnout detection. The use of multiple sensors provides redundancy in case of sensor failure. The product will use the inertial sensor technology expected to become dominant in the future.

Our present goal is to produce a $2000-3000 MSIMS that improves the accuracy of DGPS navigation, allows navigation in areas with adequate DGPS signals, and detects switching between parallel tracks. Our long-term goal is to use expected future technology to produce an under-$2000 MSIMS that provides the performance of a 1-deg/hr conventional IMS.

ENSCO intends to market the MSIMS through licensing agreements, direct sales to commercial customers, and through teaming partners. The low-cost IMS market is a natural extension of ENSCO’s current products and services which include:

* Signal processing research and applications for seismology and geophysics,
* Radar engineering and research including recent advances in ground probing radars, and
* Anti-jam GPS antenna research using digital beam forming and adaptive nulling techniques.

ENSCO considers the MSIMS market an important component of our business growth plans for the next five year time frame. We are positioned well for the future and ENSCO expects to be successfully producing low-cost IMSs for the military and commercial markets within five years. The following key management and technical personnel will be responsible for ensuring that the MSIMS becomes a successful product.

* Dr. Fred Riewe: Principal Investigator for the present project.
* Mr. Brian E. Mee: ENSCO Director of Technology Development and investigator for the present project.
* Mr. Bob Lane: Director of Strategic Business Development. Currently working with the commercialization of three other projects in the Florida Office, including two SBIRs.
* Dr. Greg Taylor: Division Manager for the Aerospace Sciences and Engineering Division.

* Mr. Jim Faist: Project Manager for Electronic Systems Development. Presently developing commercialization of Wind Profiler SBIR and Photonics projects.
* Dr. John Warburton: Vice President for Strategic Business Development. A recent accomplishment is the successful ENSCO commercialization of DataCase (a compact data collection unit).
* Mr. Kevin Kesler: Deputy Director of the Applied Technology and Engineering Division. Currently commercializing the GRMS technology developed by FRA, VNTSC, and ENSCO.
* Ms. Joyce Wenger: Director of Product Commercialization. Currently working to improve the process and reduce the time required for ENSCO to move R&D success to the commercial marketplace. Heading a commercialization effort of the Remote Ride Quality System developed under FRA R&D funding.

ENSCO's most recent success in commercialization has been with the Meteorological Monitoring System. This system, designed using expert system technology, combines atmospheric conditions with operational constraints to alert NASA and Air Force personnel at Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center to potentially dangerous conditions. Recently we have integrated our system with other operational capabilities at CCAFS and are marketing the product to the electric power and air quality industries.

6. CONCLUSIONS

The two most important characteristics of an inertial measurement system for locomotive navigation are the ability to determine location along a track and to detect switching to a parallel track. Field testing clearly indicated the capability of detecting movement to a parallel track. Our analysis indicates that the present system should be able to detect switching at speeds under 10 mph and with recently available sensors, the speed could be below 1-2 mph. The combined sensor system, including DGPS, inertial sensors, and wheel tachometer, appears to be more accurate and reliable than any system based on only a single sensor type.

This project produced the following significant findings:

- low-cost MEMS accelerometers are practical for replacing more expensive single accelerometers,
- simulations showed that combining sensors with multiple ranges can provide increased accuracy,
- pairs of accelerometers can be used to measure angular velocity, and
- use of a long baseline to separate accelerometers improves accuracy of rotational measurements.

This project explored the concept of a low-cost inertial navigation system for locomotives using multiple MEMS accelerometers. We demonstrated that multiple low-cost accelerometers can be combined to produce a system that has lower cost and greater dependability that conventional systems without reducing accuracy. Our methods can be used to produce a commercial product for applications in positive train separation and control.

7. INVESTIGATOR PROFILE

7.1 PRINCIPAL INVESTIGATOR

Dr. Fred Riewe is Chief Scientist of the Aerospace Sciences and Engineering Division of ENSCO, Inc. He has a Ph.D. in physics from the University of Florida. His current responsibilities include scientific analysis, signal processing, algorithm evaluation, statistical analysis, data simulation, test tool development, and independent testing of software systems. He is a deputy project manager for the PET&S (Performance Evaluation, Test and Simulation) contract for independent support of Eastern Range Safety systems. He is principle investigator for an IDEA contract to develop an inertial measurement system for locomotive navigation for the Transportation Research Board (TRB) of the National Research Council (NRC) and he is performing algorithm analysis for the development of an anti-jam GPS system under contract to Eglin Air Force Base. He has also developed statistical forecasting techniques for the Applied Meteorology Unit at Cape Canaveral Air Force Station under contract with the National Aeronautics and Space Administration (NASA). Dr. Riewe acts as a consultant in the fields of physics, mathematical modeling, and advanced computer programming. From 1978 to 1990, Dr. Riewe performed nuclear treaty monitoring under a contact with the Air Force Technical Applications Center (AFTAC). His work included development and analysis of atmospheric physics models, remote estimation of effluent releases, and atmospheric background modeling. He has also performed multiple regression analysis of simulated and actual atmospheric transport and diffusion. Dr. Riewe has published 12 papers in refereed professional journals and has written numerous conference papers and technical reports. Recent accomplishments include:

* Performed detailed analysis of all documented algorithms for the Distributed Range Safety Displays (DRSD) system, including the extended Kalman filter. Provided design information and independent evaluation for the next phase of the Kalman filter development.
* Analyzed MEMS accelerometer data under an ENSCO IR&D project to determine sensor characteristics.
* Analyzed implementation of DRSD $\alpha\beta\gamma$ filter.
* Developed WISE (Windows Interactive Simulation Environment) for trajectory simulation.
* Performed independent testing and performance evaluation of the DRSD system with emphasis on Kalman filter performance.

7.2 OTHER KEY PERSONNEL

In his work as Principal Investigator, Dr. Riewe was supported by ENSCO Staff Scientist Mr. Manuel Perez, ENSCO Director of Technology Development Mr. Brian E. Mee, and independent consultant Mr. Harry Gaines.

Manuel Perez, ENSCO Staff Scientist, has an M.A. in Physics from the State University of New York at Buffalo. He has performed digital filter design and analysis over the past 18 years. He has 26 years experience in analysis, testing, and software system development. At ENSCO, Mr. Perez performed analysis and has provided design information for Kalman filters and other algorithms in critical missile tracking systems on the Eastern Range. He developed the ENSCO Digital Filter Workstation, which he used for analysis of Eastern Range tracking data and for an ENSCO IR&D project to analyze MicroElectroMechanical systems (MEMS) accelerometer data. He implemented all navigation and Kalman filtering algorithms in an IDEA project for locomotive navigation. From 1993 to 1995, he was at INFOTEC Development, Inc., where he designed, coded, tested, and documented the Radar Algorithm Software Evaluation Analysis Tool (RASEAT) to generate simulated radar data to analyze Joint STARS system performance. From 1987-1993 he was at Grumman Corp., where he designed, coded, tested, and documented a Coupling Data Unit (CDU) simulator to interface with the Joint STARS Inertial Navigation Unit. From 1979 to 1987 he was Principal Systems Engineer at Honeywell Inc. There he was Technical Manager for the Alternate Inertial Navigation System (AINS) Simulator. He performed numerous systems analyses for the Shuttle Centaur program, including Gyro Torquing Uncertainty, Torquer Scale Factor Asymmetry, and Long Term Performance Stability. From 1972 to 1979, he was at Rockwell International, where he performed a study of platform compliance error for the MM III missile. He performed statistical analyses on the sensor's data for MM II and III. He designed and wrote a major part of the Sonar Processing Improvement Program.

Brian Mee, ENSCO Director of Technology Development, has M.S. and B.S. degrees in Aeronautical Engineering from Wichita State University. He has 20 years experience as a professional engineer in research, development, testing, certification, and analysis. For the last four years he has been using inertial and GPS measurements to obtain high technology solutions to railroad applications. He was responsible for testing accelerometers and gyros for use on instrumented railroad vehicles. He has been using inertial measurements to test the ride quality of high speed passenger trains in support of the Federal Railway Administration Office of Research and Development and the Office of Safety. He has conducted extensive tests of carbody acceleration on high speed rail vehicles to determine passenger ride quality. He developed a system using GPS to provide location and speed information as input to portable railroad testing equipment. He has performed testing on rail vehicles of several systems for applying differential corrections to this GPS information.

Harry Gaines is an independent consultant for digital filter design and inertial measurement system design and analysis. He is a retired Senior Engineering Fellow from Honeywell, Inc. Mr. Gaines has an M.S. in Mathematics from Florida State University. He has 35 years experience with development and analysis of inertial navigation systems and Kalman filters.

8. ACRONYM LIST

A/D	Analog-to-Digital	INS	Inertial Navigation System
ALD	Automatic Location Detector	ITS	Intelligent Transportation Systems
ARL	Army Research Laboratory	MEMS	MicroElectroMechanical Systems
ASIC	Application Specific Integrated Circuit	MSIMS	Multiple Sensor IMS
COTS	Commercial Off The Shelf	NAS	National Academy of Sciences
DGPS	Differential GPS	NRC	National Research Council
EMI	ElectroMagnetic Interference	OBC	On Board Computer
FOG	Fiber Optic Gyro	OBP	On Board Platform
FPGA	Field Programmable Gate Array	PROM	Programmable Read Only Memory
FRA	Federal Railroad Administration	PTC	Positive Train Control
GPS	Global Positioning System	PTS	Positive Train Separation
GRMS	Gage Restraint Measurement System	RLG	Ring Laser Gyro
HSR	High Speed Rail	TGMS	Track Geometry Measurement System
IDEA	Innovations Deserving Exploratory Analysis	TRB	Transportation Research Board
IMS	Inertial Measurement System	UTC	Universal Time Coordinated

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