IDEA

Innovations Deserving
Exploratory Analysis Programs

High-Speed Rail IDEA Program

Low-Cost Multiple Sensor Inertial Measurement Product for Locomotive Navigation

Final Report for High-Speed Rail IDEA Project 27

Prepared by:
Fred Riewe, Principal Investigator
ENSCO, Inc.

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TRANSPORTATION RESEARCH BOARD
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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Low-Cost Multiple Sensor Inertial Measurement Product for Locomotive Navigation

IDEA Program Final Report
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IDEA HSR-27

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Fred Riewe, Principal Investigator
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ABSTRACT

There is an increasing need to accurately determine the position of a locomotive along a track for advanced train control systems such as Positive Train Control. For locations where GPS (Global Positioning System) reception is not adequate, inertial navigation can provide the needed information. However, existing inertial navigation systems may be prohibitively expensive due to the high cost of the inertial sensors. The overall goal of this project was to develop an inertial navigation system capable of accurately determining the location of a locomotive while using inexpensive MicroElectroMechanical Systems (MEMS) sensors. Navigation and Kalman filtering software was developed with innovative features to improve the performance of the low-cost sensors for rail applications. The algorithms and software were successfully tested with simulated data and verified by the use of recorded data. An inertial measurement system using MEMS accelerometers and gyros was developed and tested. However, the accuracy of the inertial system was too low for it to be used for successful navigation.

Keywords: inertial navigation, positive train control, positive train separation, MEMS, inertial sensors, Kalman filter

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1. EXECUTIVE SUMMARY

Figure 1. Challenge facing locomotive inertial navigation systems. (Photo taken during ENSCO IDEA Type 1 contract field testing.)

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. The importance (and complexity) of determining locomotive location is illustrated by Figure 1. The overall goal of the present project and its predecessor was to develop an inertial navigation system (INS) capable of accurately determining the location of a locomotive using inexpensive MicroElectroMechanical Systems (MEMS) sensors and GPS (Global Positioning System) positioning. An earlier ENSCO IDEA concept exploration (Type 1) project demonstrated that it is feasible to design a low-cost INS capable of detecting track switching. The present IDEA product application (Type 2) project, along with ENSCO Independent Research and Development (IR&D), developed specifications, algorithms, simulators, software, and a complete Kalman filtering and navigation software system called GINIUS, for GPS Inertial Navigation Instrument Universal System. The software was first developed for non-real-time operation and was then modified and implemented on a real-time computer system. An inertial measurement system (IMS) was assembled using MEMS accelerometers and gyros. However, the MEMS sensors proved to lack the required accuracy, so the completed system was unable to provide suitable navigation.

The development of the GINIUS system began with a requirements-definition phase. The requirements are based on the need to support PTS and PTC applications. These include requirements for navigation and Kalman filter algorithms, calibration, real-time software, operating system, and hardware. Under separate IR&D funding, ENSCO developed the algorithms and their non-real-time software implementation. These requirements and specifications have been compiled in three documents, *System Specification for the GPS Inertial Navigation Instrument Universal System (GINIUS)*, *System Architecture Description for the GPS Inertial Navigation Instrument Universal System (GINIUS)*, and *Algorithm and Performance Requirements for the GPS Inertial Navigation Instrument Universal System (GINIUS).* We then evaluated sensor technology advances. We found that the Analog Devices, Inc. accelerometers and gyros identified in the proposal remained the best choice. No improved sensors had become available since the completion of the concept exploration (Type1) project. New algorithms were developed under ENSCO Internal Research and Development (IR&D) funding and presented in a series of ENSCO internal documents. These algorithms include the use of speed sensor data and map information, the ability to freeze position and orientation when the locomotive's motion has stopped, a method of constraining lateral motion predictions, a method of calculating the distance traveled along the track, and the ability to accept discrete position data, as from a transponder or rail detector.

All algorithms were incorporated into the navigation and Kalman filter software. All algorithms were tested using recorded and simulated data. It was determined that the most practical approach to software development was to keep the algorithms coded in Fortran and to perform the real-time programming in the C language. Calibration procedures were developed and described in the ENSCO internal document *Inertial Sensor Assembly Factory Calibration*. The sensor evaluation was completed and the Analog Devices ADXL105 accelerometers and the ADXRS150 gyros were found to be the most appropriate for this application based on the functional and performance requirements. The design was completed for the computer system and sensor electronics and packaging.

Figure 2. GINIUS computer system.

The computer and sensor hardware was assembled and tested. Figures 2 and 3 show the computer and sensor systems. The software was converted to C-language real-time code in which incoming data was placed in a buffer which was processed in real time using the Fortran processing software. However, when it became apparent that the assembled sensor system did not have the needed accuracy, software development was halted and the proposed field tests on a locomotive were cancelled. Additional laboratory testing was conducted using recorded data from the GINIUS IMS and independently recorded data from a Honeywell HG1700 IMS. Both sets of data were recorded using an automobile to complete a closed loop of travel. The test results indicated that successful navigation could not be performed using the GINIUS IMS. The HG1700 provided suitable accuracy, but is not a MEMS device. A similar system, the HG1900, does use MEMS gyros, but its $30K cost disqualifies it as a low-cost sensor system. Our conclusion is that it is impractical to base an inertial navigation system for locomotives on existing low-cost MEMS sensors. When suitable sensors become available, our methods should allow development of an INS optimized for locomotive navigation.

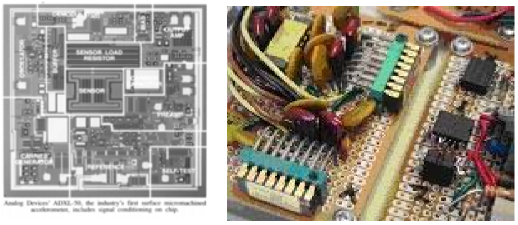


Figure 3. Microphotograph of a MEMS accelerometer, shown next to the interior of the GINIUS inertial measurement system. The accelerometer chip is 0.11 inches square and the IMS electronics is 3x4x1 inches.

This project produced the following significant results:

- development of specifications for a locomotive inertial navigation system,
- development of inertial sensor simulators,
- development and implementation of algorithms for navigation along a track, and
- development of preliminary inertial navigation software.

The GINIUS concept developed by this project differs in two areas from conventional non-locomotive inertial navigation systems.

- The system design incorporates inexpensive MEMS sensors.
- The design makes use of the one-dimensional nature of railroad track to improve performance.

The GINIUS concept has the following potential advantages over conventional non-locomotive navigation systems:

- has low-cost when implemented with MEMS sensors. (However, present MEMS sensors with the required accuracy are prohibitively expensive. The cost is expected to drop significantly, but not in the near future.)
- has small size, due to use of MEMS accelerometers,
- is optimized for railroad applications by making use of one-dimensional nature of railroad track,
- can use multiple sensors to provide redundancy in case of sensor failure (after suitable inexpensive MEMS sensors become available), and
- uses the inertial sensor technology (MEMS) that has the potential to become dominant in the future.

2. BACKGROUND AND OBJECTIVES

Several demonstration projects of advanced train control systems are underway that include a locomotive navigation function. These projects have used conventional rate gyros and laser and 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. Earlier accuracy requirements have specified 1-sigma location to within 20 feet and turnout detection within 50 feet (*1*). At the time the IDEA project began, the North American Joint PTC Program (*2*) required location accuracy to within 10 feet and speed accuracy within 0.5 miles per hour. The most recent specification requires accuracy of 10 feet or better at a confidence level of 99% and speed to within 0.5 mph. (*3*). One of the major challenges for PTC will be the development of low-cost navigation system sufficiently accurate to meet these requirements.

The GPS Inertial Navigation Instrument Universal System (GINIUS) designed by this project investigates the use low-cost accelerometers and gyros to replace the more expensive sensors used for conventional inertial systems. The GINIUS is the first step toward development of an inexpensive inertial navigation system that meets the requirements for locomotive navigation. The purpose of the GINIUS 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 GINIUS product is designed to accept GPS (Global Positioning System) or DGPS (Differential GPS) data, as well as inertial sensor, transponder, and wheel tachometer data. The objective of this IDEA project is to develop a prototype of a commercial navigation system that uses innovative methods to allow the use of inexpensive inertial sensors to provide accurate navigation at the lowest practical cost.

3. IDEA PRODUCT

There is an increasing need for smaller and more accurate Inertial Measurement Systems (IMSs) for locomotive navigation and other commercial and industrial navigation uses. 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.

In the original Type 1 IDEA proposal in 1997, 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 purchases in large quantity. The prediction was on target: In April 1999, 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 were available for under $15 in small quantities at that time and are now (2004) available for under $10. Analog Devices ADXL105 MEMS accelerometers are the sensors chosen for use in our project. They presently cost about $20 in small quantities. The project also uses Analog Devices ADXRS150 MEMS gyros, which were announced at $150 and now sell for $33 in small quantities. The availability of low-cost miniature sensors provides the opportunity to combine multiple sensors while reducing size and cost in comparison to conventional IMSs. However, the accuracy of the sensors has been driven more by applications in the automotive and related industries and not by the need for precision sensors for inertial navigation. Consequently, there has been very little improvement in MEMS accelerometer accuracy since the conclusion of our concept exploration project in April 2000.

The INS designed by this project differs in two areas from conventional inertial systems. The system uses inexpensive MEMS sensors to replace much more expensive sensor systems. It also uses a Kalman filter and navigation system that makes use of the one-dimensional nature of railroad track to improve accuracy. An added benefit of using low-cost sensors is that it may be cost effective to use multiple sensors, so that a system would be able to function even with the loss of one or more sensors.

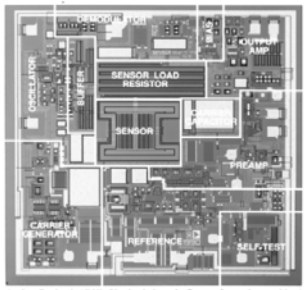
Low-cost inertial systems have potential applications that previously have not made use of inertial technology due to cost or performance tradeoffs. In the railroad industry alone, use of low-cost INSs can give precise positioning capability to locomotives; specialized maintenance of way vehicles such 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.

4. CONCEPT AND INNOVATION

This project explored the concept of a low-cost inertial navigation system for locomotives using MEMS accelerometers and gyros. We investigated the question of whether low-cost sensors can be used to produce a system that has lower cost and greater dependability than conventional systems. Innovative methods were used to compensate for the reduced accuracy of the low-cost sensors. However, as described below, the accuracy of low-cost MEMS sensors is still not sufficient to provide accurate navigation.

The GINIUS Kalman filter and navigation software has features designed specifically for locomotive navigation, such as map information and lateral constraint. These features are designed to make use of the one-dimensional nature of railroad track to increase accuracy in compensation for the reduced accuracy of MEMS accelerometers and gyros. In addition to the standard navigation ability of a conventional navigation system, it has the following combination of innovative features. These features are described in more detail later in the report.

1. Use of speed sensor data (such as from a wheel tachometer or Doppler radar) to improve position determination in the direction of motion along a track.
2. Use of map information, such as the track databases maintained by many railroads, to improve position determination in the direction perpendicular to the track. The combination of map information and speed sensor data improves accuracy in all horizontal directions.
3. Ability to freeze position when an indicator (such as a speed sensor) determines that there is no motion.
4. Ability to freeze azimuth when the speed is zero. We use an innovative method that supplies azimuth information to a special state of the Kalman filter. Since roll and pitch angles are automatically frozen at zero speed as a standard feature of the Kalman filter, the combination of freezing position and azimuth prevents any position or orientation change when a locomotive is stopped, even when GPS is unavailable, as is often the case in a station.
5. Constrains first-order lateral motion predictions. This improves accuracy by making use of the knowledge that a locomotive has no first-order motion perpendicular to the track.
6. Calculates distance traveled along the track to serve as odometer.
7. Accepts discrete position data, as from a transponder or rail detector.



Analog Devices' ADXL-50, the industry's first surface micromachined accelerometer, includes signal conditioning on chip.

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

The basis of this project is the concept of using MEMS sensors to replace conventional accelerometers and gyros. 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*).

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 has been the automotive industry. Accelerometers are used to determine air bag deployment and are finding 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 the 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.

The IMS developed for this project uses MEMS accelerometers from Analog Devices. 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 chip is approximately 0.11 inches square, with the sensor located in the center. The accelerometer selected for this project is the Analog Devices

ADXL105, which has improved sensitivity in comparison to the ADXL50 or theADXL150/250 accelerometers used in the IDEA Type 1 project.

MEMS gyros have been produced in laboratory settings and commercial units are now available. Most rely on the principle that vibrating elements will detect the Coriolis effect when the device is rotated. An example, from Analog Devices, is shown in Figure 5. Rotating MEMS gyroscopes have also been designed and their rotors have been built and tested (*7*), but they are considered to be impractical and are not expected to be commercially available. A number of inexpensive non-MEMS vibrating gyros have been available commercially. For example, Murata manufactures the ENV-05 Gyrostar piezoelectric ceramic gyroscope. During the IDEA Type 1 project, ENSCO added three ENV-05 gyros to the laboratory evaluation system to obtain a complete six-degree-of-freedom sensor system. Draper Laboratory (*8*) developed MEMS gyros over a period of about eight years. Resolution has steadily improved by roughly a factor of 10,000 over that time span (*9*). The Draper Laboratory's gyro is now available as a component of the Honeywell HG1900 IMS. However, the present cost for an HG1900 is about $30K, making it impractical for the present project. Relatively inexpensive MEMS gyros are now available from Analog Devices (*10*).

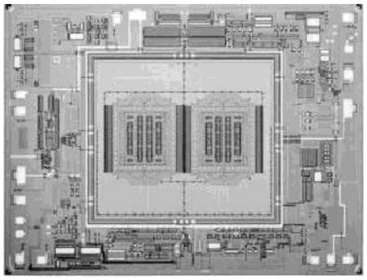


Figure 5. MEMS gyro developed by Analog Devices, Inc.

Unfortunately, there has been very little improvement in MEMS accelerometer accuracy since the time of our original IDEA Type 1 proposal in 1997. Our Type 1 IDEA project found methods of combining sensors with differing characteristics, but the needed sensors have not appeared. Presently available MEMS gyros either lack the needed accuracy or are more expensive than conventional gyros. When appropriate MEMS sensors become available, our methods can be used to produce a commercial product for applications in positive train separation and control.

5. INVESTIGATION

5.1 OVERVIEW

Under the IDEA contract HSR-27, ENSCO's Aerospace Sciences and Engineering (ASE) Division has been developing an Inertial Navigation System (INS) that uses MicroElectroMechanical Systems (MEMS) sensors as inexpensive alternatives to traditional accelerometers and gyros. Absolute position is determined using the Global Positioning System (GPS). The system is called GINIUS, which stands for GPS Inertial Navigation Instrument Universal System. (The system was originally named GINI, but that name was later found to be trademarked.) GINIUS uses a Kalman filter to process sensor information and provide navigation results. ENSCO internal research and development (IR&D) funding was used to develop the algorithms and software, using innovative methods to overcome limitations of the MEMS sensors. The system can be used for any type of vehicle or mobile device, but has innovative capabilities aimed specifically at locomotives. The goal of the IDEA project is to develop a prototype of a commercial GINIUS system that uses advanced Kalman filter and navigation algorithms to process inertial data from MEMS accelerometers and gyros.

The project was performed in two phases. The first phase (Type 1 IDEA Contract HSR-14), which was completed in 2000, explored the concept of developing an inertial navigation system for locomotives. Parallel to that phase, ENSCO began the development of Kalman filter and navigation algorithms used to process recorded data from INS hardware. We demonstrated that the IDEA system could successfully display an inertial signature indicating that a locomotive has switched to a parallel track. In the second phase (present Type 2 IDEA Contract HSR-27), which began in June 2001, we developed a prototype INS that provides real-time navigation information. The overall goal is to use innovative methods to use MEMS sensors to provide an accurate navigation system at the lowest practical cost.

This section describes progress and results throughout the present Type 2 contract. The project consisted of three stages:

Stage 1

- Define navigation and Kalman filtering algorithm requirements and develop new algorithms.
- Define calibration requirements and develop calibration algorithm.
- Define real-time software requirements and operating system requirements.
- Evaluate sensor technology advances. Define hardware requirements for the IMS.

Stage 2

- Develop navigation and filtering algorithm software and test with recorded data.
- Develop calibration procedures.
- Choose implementation language for real-time system and code real-time non-algorithm software.
- Complete the review of available sensors and choose sensors for testing.
- Design electronics and packaging of the IMS.

Stage 3

- Code and test real-time software for the prototype.
- Perform laboratory testing of the inertial sensors.
- Assemble prototype and conduct laboratory shakedown tests.
- Finalize the field test plan and perform field testing of the IMS, including analysis of field test data versus the performance goals for the project. (The field test was to be conducted by installing the INS in a locomotive. It was replaced by additional laboratory testing using simulated and recorded data when shakedowns testing revealed that the low-cost MEMS sensors could not provide the needed accuracy.)

5.2 REQUIREMENTS, ARCHITECTURE, AND ALGORITHM DEVELOPMENT

The project began with the development of requirements and architecture for the GINIUS system. These specifications include requirements for navigation and Kalman filter algorithms, calibration, real-time software, operating system, and hardware. Under separate IR&D funding, ENSCO developed the algorithms and their non-real-time software implementation. These requirements and specifications have been compiled in three documents, *System Specification for the GPS Inertial Navigation Instrument Universal System (GINIUS)*, *System Architecture Description for the GPS Inertial Navigation Instrument Universal System (GINIUS)*, and *Algorithm and Performance Requirements for the GPS Inertial Navigation Instrument Universal System (GINIUS).* These documents are summarized in the following sections.

5.2.1 System Specification

We have specified system requirements for GINIUS in a document entitled *System Specification for the GPS Inertial Navigation Instrument Universal System (GINIUS)*. This document provides system-level real-time software requirements, hardware requirements, and operating system requirements. 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. A table of requirements and qualification methods from the document is given below.

The following requirements and their qualification methods are extracted from the System Specification document.

DEMONSTRATION: A verification method relying on observation of an item performing its specified function under a specific set of conditions. This does not require the use of instrumentation or special test equipment.

INSPECTION: Verification by visually examining an item, reviewing the descriptive documentation, and comparing appropriate characteristics with a predetermined or referenced standard to determine conformance to specific requirements.

ANALYSIS: Verification by technical or mathematical evaluation using mathematical equations, algorithms, or models; the use of charts, diagrams and representative data; or evaluation of previously qualified equipment.

TEST: Verification using instrumentation of an item performing its specified function. This involves the systematic exercise of the test item under all applicable conditions and measuring its specified parameters. Acceptability of the item under test is determined by evaluation of the measured data against predetermined performance requirements.

Table 1. Requirements and qualification methods

No.	Requirement	Qual
1	The Idle state shall (1) provide for the acceptance of operator inputs relevant to the operation of the system.	T
2	While in the Idle state, GINIUS shall (2) output a valid state vector indicating the last known state or a default vector.	AT

3	GINIUS shall (3) produce a report identifying the following conditions in the simulated source data: Missing data based on time information; Corrupted checksums, if any; Corrupted or missing synchronization patterns, if any	T
4	The Processing state shall (4) provide a display to allow an operator to determine the status of the real-time run.	DT
5	This display shall (5) include present time, recorded data time (if recorded data), and state vector information.	AT
6	The Recorded-Data Playback Mode shall (6) be entered upon operator command from the Idle State.	T
7	In this state, GINIUS shall (7) read data from a file.	AT
8	It shall (8) generate and output as a file the time and state vector.	AT
9	GINIUS shall (9) return to the Idle state at the end of recorded data.	T
10	It shall (10) also return to the Idle state upon operator command.	T
11	If there is a Real-Time Data Mode, then it shall (11) be entered upon operator command from the Idle State.	T
12	In the Real-Time Data Mode, GINIUS shall (12) accept data from hardware input devices.	T
13	It shall (13) generate and output as a file the time and state vector.	T
14	GINIUS shall (14) return to the Idle state upon operator command.	T
15	In the Simulation state, GINIUS shall (15) produce an output file of simulated or prerecorded data.	T
16	In the Simulation state, GINIUS shall (16) not require input data.	T
17	GINIUS shall (17) return to the Idle state upon operator command.	T
18	GINIUS shall (18) read recorded data from disk files from internal, external, or network drives.	T
19	The data file shall (19) be an ASCII text file in a format to be determined.	T
20	GINIUS shall (20) write recorded data to disk files on internal, external, or network drives.	T
21	The data file shall (21) be a space-delimited ASCII text file in a format readable by standard word processors and spreadsheet programs.	T
22	If there is a Real-Time Data Mode, then it shall (22) accept input data from hardware interfaced to accelerometers, to gyros (if used), and a GPS or DGPS receiver (if used).	T
23	The operator shall (23) be able to create, modify, and delete configuration data files (if any), recorded input data, and recorded output data for the system.	T
24	Storage peripherals including any hard disk drive(s), floppy disk drive(s) or tape units shall (24) be contained internally in the unit’s case.	D
25	The unit shall (25) be FCC Class B approved.	I
26	It is intended that the Reliability, Maintainability and Availability (RMA) requirements of GINIUS shall (26) provide for, at minimum, a 90% probability to support data processing functions, based on a combination of hardware and software RMA statistics.	AI
27	The GINIUS hardware components shall (27) meet the reliability of industry standard COTS small computer products.	I
28	GINIUS shall (28) be designed and developed such that, once in a operational state, the MTBF for the software will be 400 hours of operational time from implementation of a new operational version.	I
29	Once repair parts are obtained, the Mean-Time-to-Repair (MTTR) at the system level shall (29) not exceed 4 hours.	I
30	The maximum time (Mmax) shall (30) not exceed 8 hours.	I
31	The MTTR for a single software failure shall (31) not exceed 4 hours.	I
32	The maximum time (Mmax) shall (32) not exceed 8 hours.	I
33	Availability of GINIUS shall (33) be, at minimum, the following values:	I

34	GINIUS software shall (34) be designed to provide for traceability (provide a thread from requirements to implementation), consistency (provide uniform design and documentation), and completeness (provide full implementation of the required functions).	I
35	GINIUS shall (35) be capable of withstanding the following environmental extremes which are common to many of the hardware components residing in the Cocoa Beach Science and Engineering Facility :	I
36	GINIUS software shall (36) be written in a high level computer language such that existing software may be utilized for the development of the system.	I
37	The GINIUS software shall (37) be written to avoid language-specific features to allow the conversion of the software into other languages if needed for the future development of a real-time system .	I
38	All GINIUS software shall (38) contain adequate documentation to identify the system, component (module), and version of the software.	I
39	GINIUS shall (39) be composed of COTS equipment, that provides for the following safety features:	I
40	The GINIUS operator controls shall (40) be located so as to require only a single operator.	I
41	GINIUS shall (41) use a menu driven interface.	D
42	GINIUS shall (42) use at least a color screen with large type fonts (minimum 12 point) for ease of readability.	D
43	Multiple colors shall (43) be used to readily depict error and warning conditions from normal operation of the system.	T
44	The system shall (44) include all security features required for ENSCO computer equipment, including virus protections and passwords for screen savers and network access.	I
45	To permit additional processing of sensor and GPS data by GINIUS, the system shall (45) at minimum permit 100% expansion of memory.	A
46	It shall (46) provide a 30% reserve in available CPU and memory capacity.	A

5.2.2 System Architecture

We have specified the GINIUS system architecture in a document entitled *System Architecture Description for the GPS Inertial Navigation Instrument (GINIUS).* The table of contents from the document is listed below.

The following is the table of contents from the System Architecture document.

5.2.3 Algorithm and Performance Requirements

We have specified requirements for the GINIUS algorithms and performance in a document entitled *Algorithm and Performance Requirements for the GPS Inertial Navigation Instrument (GINIUS)*. This document provides performance and accuracy requirements for real-time software, hardware, the operating system, and calibration. The table of contents and requirements from the document are listed in the subsections below.

The following is the table of contents from the Algorithm and Performance Requirements document.

The following specifies the GINIUS requirements from the Algorithm and Performance Requirements document.

GINIUS Functional Requirements

- The GINIUS shall (1) record all reported data to non-volatile storage. The GINIUS may optionally report this information via a serial data stream or wireless modem link.
- The GINIUS shall (2) report location, distance traveled, direction, and speed.
- The GINIUS shall (3) monitor and report its operational state, health, and status.
- The GINIUS shall (4) be capable of autonomous operation, e.g. no operator input required to begin location/status reporting after initialization/reset.
- The GINIUS shall (5) contain sufficient storage for at least 24 hours of autonomous operation when recording location, distance, direction, and speed. For longer operational periods, it shall (6) be configurable to either halt recording when storage is exhausted or replace the oldest values with the most recent.
- The GINIUS shall (7) allow for the recording of all raw sensor input values. It shall contain sufficient storage for at least 2 hours of autonomous operation when recording raw sensor values. For longer operational periods, it shall (8) be configurable to either halt recording when storage is exhausted or replace the oldest values with the most recent.

Power-up and Initialization

- The GINIUS shall (9) determine the hardware integrity of each GINIUS module upon power-up or reset (Power on self-test) and report any failures.
- The GINIUS shall (10) determine the software integrity of each module upon power-up (report version number or checksum).

- The GINIUS shall (11) report degraded performance until all navigation sensors report good position information.
- The GINIUS shall (12) allow the following parameters to be set at system initialization:
  - Current wheel diameter
  - Offset of the GPS location reference point (e.g. antenna) to the locomotive location reference point.

Determination of Location, Direction, and Speed

- The GINIUS shall (13) determine the direction of travel of the locomotive relative to a defined direction (e.g. movement in the direction of the short hood = direction A, movement in the direction of the long hood = direction B). This information shall (14) be independent of the reverser (handle) contact, which gives the activated direction of the locomotive.
- The GINIUS shall (15) maintain a distance ripple counter which will be incremented in direction A and decremented in direction B. The distance ripple counter shall (16) be set to 0 upon GINIUS initialization.
- The GINIUS shall (17) determine the 2D geodetic position (i.e., latitude and longitude) of the reference point of the locomotive.
- The GINIUS shall (18) determine the speed of the train along the track within a range of 0 to 125 miles per hour.
- The GINIUS shall (19) calculate the confidence interval of the distance ripple counter value in both direction A and direction B.
- The GINIUS shall (20) calculate the confidence interval of the 2D location.

Reporting of Location, Direction, Speed and Status

- The GINIUS shall (21) time stamp all reported data with the current time to the nearest millisecond.
- The GINIUS shall (22) report the current distance counter value along with the confidence interval.
- The GINIUS shall (23) report the current speed (with confidence interval) of the locomotive.
- The GINIUS shall (24) report the direction of travel (A or B).
- The GINIUS shall (25) report which sensors types contributed to the location and speed values.
- The GINIUS shall (26) report current speed, distance, location, and direction at a rate of 1 Hz.

Physical Requirements

The GINIUS will be constructed to operate in a railroad locomotive cab or equipment bay environment. The GINIUS will use extended temperature parts wherever feasible. It will not require external cooling or airflow. The GINIUS will be designed to meet FCC Class-A radiated EMI requirements.

- The GINIUS shall (27) support both permanent and temporary attachments in any orientation.
- The GINIUS shall (28) only require power and GPS antenna connections to generate and record position data.
- The GINIUS shall (29) operate on 12-volt power. The GINIUS will also support 72-volt locomotive power or internal battery power if external 12-volt power is not available.

GINIUS Performance Requirements

- The inertial data shall (30) 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 (31) be processed at a high enough frequency (approximately 10 Hz) to accurately update the state vector solution.
- The GPS/DGPS update shall (32) 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.

GINIUS Calibration Requirements

Calibration means the determination of the parameter values to be used to correct the sensor output for systematic errors. Calibration will be performed when GINIUS is assembled and will not be necessary during installation.

Factory calibration requirements

- Calibration procedures shall (1) determine the accelerometer bias errors, accelerometer scale factor error and mutual misalignment of the accelerometers.
- Calibration procedures shall (2) determine the gyro bias errors, gyro scale factor errors, and misalignment of each gyro with respect to the accelerometers.
- Calibration hardware shall (3) consist of a calibration frame, a calibration plate, and a standard desktop or laptop computer.

User calibration requirements

- GINIUS shall (4) require no user calibration after installation unless there is a change to the hardware.
- GINIUS shall (5) be capable of recalibration after hardware changes using only the factory calibration procedures.

GINIUS Accuracy Requirements

The GINIUS navigation design goal will be to determine the location of the leading edge of the controlling locomotive along the track with an accuracy of 10 feet or better at a confidence level of 99%. This requirement is based on *North American Joint Positive Train Control Program, IDOT PTC Project, Software Requirements Specification*, Document No. SD-19-17018 (NP), Rev. B, 24 September 2003.

- Position shall (33) 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 (34) be regained within 5 Kalman filter cycles.
- When provided with accurate accelerometer data, GINIUS shall (35) provide position, velocity, and acceleration data accurate enough such that the probability of correct track determination when passing through a turnout is on the order of seven sigma at speeds of 0.1-125 miles per hour or greater.
- If GPS/DGPS becomes unavailable, GINIUS shall (36) 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. Future versions of GINIUS are expected to employ additional data, such as map information or wheel tachometer data for additional stability and accuracy.

5.3 GINIUS ALGORITHMS AND SIMULATIONS

Algorithms and their software implementation have been developed. The following new filter and navigation algorithms were developed:

- Use of speed data (wheel tach or Doppler radar)
- Use of map data
- Calculation of confidence radius and along-track confidence interval
- Calculation of along-track distance
- Elimination of accelerometer drift in a motionless vehicle
- Elimination of gyro drift in a motionless vehicle
- Constraint to zero lateral motion of vehicle (implemented, but not fully tested)

We have specified GINIUS algorithms for navigation, Kalman filtering, calibration, and simulation in the following ENSCO internal documents:

- *Algorithms for Kalman Filter Aided Inertial Navigation* (25 pages, 79 equations)
- *Navigation by Truck Angle, GPS, and Wheel Tach* (11 pages)
- *Speed Observation* (3 pages, 5 equations)
- *Map Observation* (4 pages, 7 equations)
- *2- and 3-dimensional* R(p) (4 pages, 9 equations)
- *Approximate R(p)* (1 page, equations not numbered)
- *Along-Track Forward Distance* (5 pages, 5 equations)
- *Inertial Sensor Assembly Factory Calibration* (19 pages, 10 equations)
- *Simulating Continuous Gaussian White Noise* (2 pages, equations not numbered)
- *Simulating a First Order Markov Process* (2 pages, equations not numbered)

- *Corrected Attitude Algorithm Improvement* (1 page, equations not numbered)
- *Freeze Azimuth Observation* (5 pages, equations not numbered)
- *Notes on the Zero Lateral Velocity Observations* (4 pages, equations not numbered)

We developed the MultiSim simulator for testing GINIUS software. The simulator has the following features:

- Dynamic simulation, based on trajectory (geodetic or earth fixed geocentric) data
- Static simulation, compatible with the static simulator developed for the Type 1 project
- Attitude simulation (roll, pitch, heading)
- Geometric trajectory simulation (lines, circles, curves)
- Noise and bias simulation
- Initial and intermediate trajectory data smoothing
- File interchange, conversion, and modification
- Plotting within simulator
- External Mathcad plot software for file comparison and analysis

5.4 PANEL MEETING AND PANEL OF ADVISORS

We selected and convened a panel of user representatives, technical experts, and system integrators to review system requirements, architecture, test criteria, and approach. The panel meeting was held the afternoon of 25 April 2002 at the ENSCO Corporate Offices in Springfield Virginia. The panel members were:

1. Denny Lengyel, ARINC (Technical Advisor)
2. Richard Cataldi Manager-Operations Support, Virginia Railway Express
3. Michelle White, Navigation Team Project Manager, AFRL/MNGN, Eglin Air Force Base (did not attend)
4. Ralf Wennrich, Manager Wayside Control Systems, Siemens Transportation Systems
5. Denise Lyle, Director, Advanced Train Control Projects, CSX Transportation (unavailable due to travel)
6. One of the following: (unavailable due to last-minute schedule conflicts)
    - Ruben Payan, Electrical Engineer, NTSB Office of Railroad Safety.
    - Patrick Sullivan, Railroad Accident Investigator, Signal Specialist, NTSB Office of Railroad Safety.

Other attendees for all or part of the meeting:

- Chuck Taylor, TRB
- Brian Davies, ENSCO
- Eddie Malinowicz, ENSCO
- Brian Mee, ENSCO
- Fred Riewe, ENSCO
- Greg Taylor, ENSCO
- Ta-Lun Yang, ENSCO

5.5 TRB ANNUAL MEETING SUPPORT

We provided a poster for display at the TRB annual meeting in January 2002. The poster from the original Type 1 IDEA program, which had been prepared for a previous TRB meeting, was out of date. We produced an up-to-date poster illustrating concepts from the present IDEA Type 2 contract.

5.6 GINIUS ALGORITHM AND SIMULATOR DEVELOPMENT

The following new filter and navigation algorithms were developed and implemented:

- Use of speed data (wheel tach or Doppler radar)
- Use of map data
- Calculation of confidence radius and along-track confidence interval

- Calculation of along-track distance
- Elimination of accelerometer drift in a motionless vehicle
- Elimination of gyro drift in a motionless vehicle
- Constraint to zero lateral motion of vehicle (only partially implemented)
- Use of Transponder data (only partially implemented)

We have specified GINIUS algorithms for navigation, Kalman filtering, calibration, and simulation in the following ENSCO internal documents:

- *Algorithms for Kalman Filter Aided Inertial Navigation* (25 pages, 79 equations)
- *Navigation by Truck Angle, GPS, and Wheel Tach* (11 pages)
- *Speed Observation* (3 pages, 5 equations)
- *Map Observation* (4 pages, 7 equations)
- *2- and 3-dimensional* R(p) (4 pages, 9 equations)
- *Approximate R(p)* (1 page, equations not numbered)
- *Along-Track Forward Distance* (5 pages, 5 equations)
- *Inertial Sensor Assembly Factory* Calibration (19 pages, 10 equations)
- *Simulating Continuous Gaussian White Noise* (3 pages, equations not numbered)
- *Simulating a First Order Markov Process* (2 pages, equations not numbered)
- *Corrected Attitude Algorithm Improvement* (1 page, equations not numbered)
- *Freeze Azimuth Observation* (5 pages, equations not numbered)
- *Notes on the Zero Lateral Velocity Observations* (4 pages, equations not numbered)
- *Transponder Observation* (7 pages, 15 equations)

Using ENSCO IR&D funding, we developed the MultiSim simulator for testing GINIUS software. The simulator has the following features:

- Dynamic simulation, based on trajectory (geodetic or earth fixed geocentric) data
- Static simulation, compatible with the static simulator developed for the Type 1 project
- Attitude simulation (roll, pitch, heading)
- Geometric trajectory simulation (lines, circles, curves)
- Noise and bias simulation
- Initial and intermediate trajectory data smoothing
- File interchange, conversion, and modification
- Plotting within simulator
- External Mathcad plot software for file comparison and analysis
- Interfaces to AutoSensorLab GPS simulator and MatLab Kalman filter implementation.

5.7 NAVIGATION AND FILTERING SOFTWARE DEVELOPMENT AND TESTING

ENSCO developed, implemented, and tested navigation and Kalman filtering algorithms. These algorithms are provided in a series of internal ENSCO documents. The main document is entitled *Algorithms for Kalman Filter Aided Inertial Navigation*. The complete list of documents is provided in Section 5.6. The algorithms are presented in sufficient detail to allow the navigation and filtering software to be developed directly from the documents. All algorithms have been implemented in software. All have been successfully tested, except for the zero-lateral-velocity algorithm, which is not required for field testing. The zero-lateral-velocity algorithm has been coded, but did not provide improvement to the navigation.

The navigational and filtering elements are central to the GINIUS system. They process input sensor and GPS data and provide smooth position and orientation outputs. A Kalman filter is also ideal for integrating inputs from sensors with differing characteristics. For GINIUS, we are using the Kalman filter developed in the Type 1 IDEA Project and have extended it to support speed sensor (wheel tachometer or Doppler radar) data, map information, and discrete location data from transponders and turnout detectors. Figure 6 shows a block diagram of the GPS-aided navigation and Kalman filtering system. The shading indicates components developed during the Type 1 project and the cross hatching shows components developed with ENSCO IR&D before or during this Type 2 project. The transponder algorithm, which is not required for field testing, has been developed and implemented, but it has been tested with nominal data only. (Independent of the IDEA project, we also had considered the implementation of an algorithm to make use of truck angle data, but it has not been completely developed or implemented.)

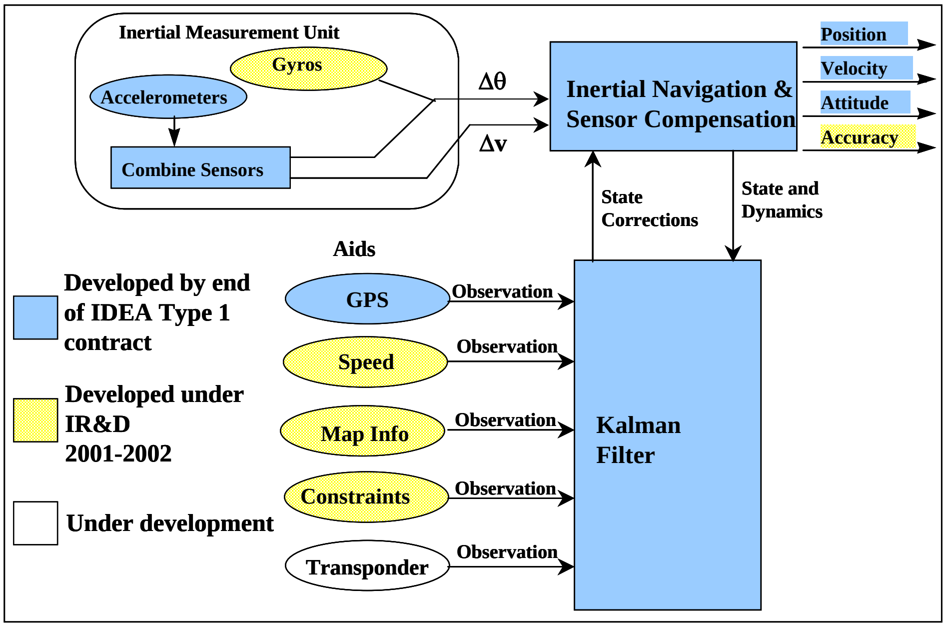
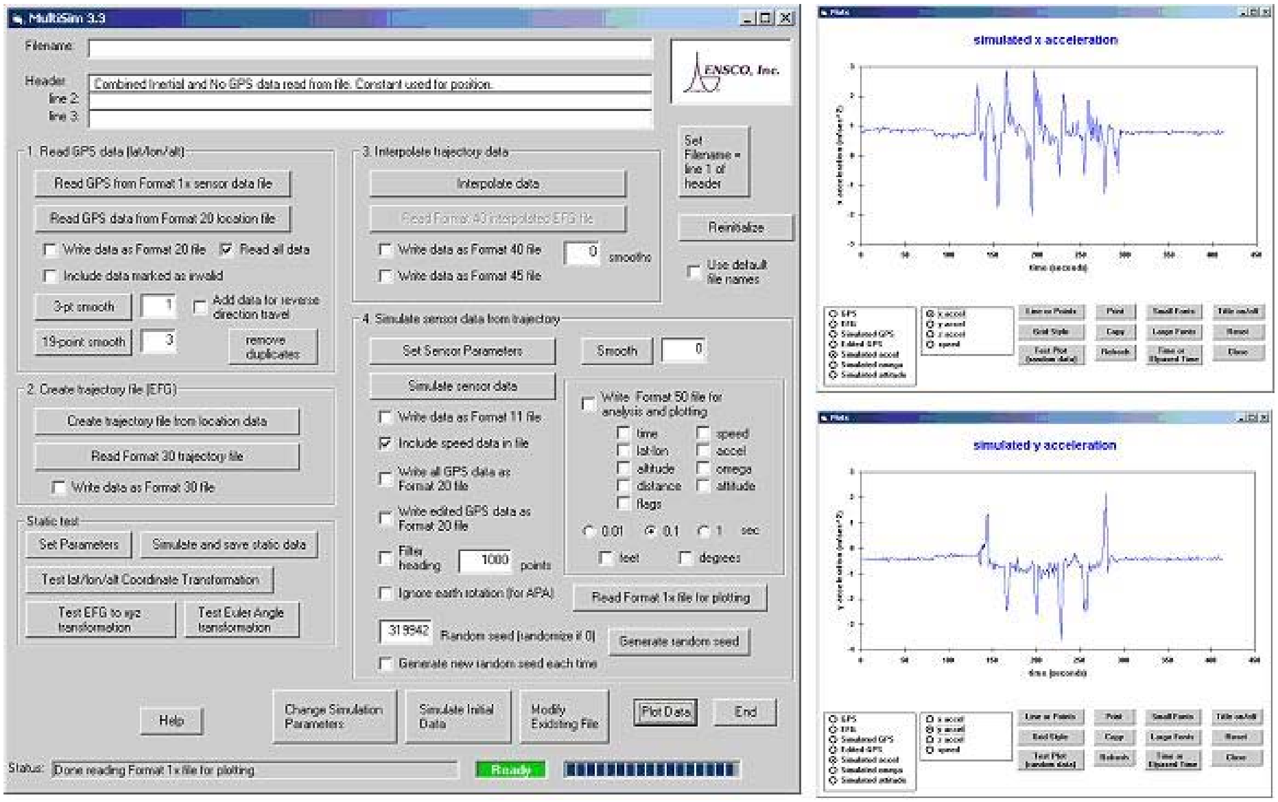


Figure 6. Configuration for navigation and GPS-aided Kalman filtering.

For checkout and testing of the navigation and Kalman filter software, we have developed simulation software that makes use of recorded or internally calculated position data to generate simulated sensor data. The simulator was developed with ENSCO IR&D funding, at no cost to the IDEA program. The front panel of the simulator and examples of the built-in plotting capability are shown in Figure 7.



Header: Combined Inertial and No GPS data read from file. Constant used for position.
line 2:
line 3:

☐ Write data as Format 20 file ☑ Read all data
☐ Include data marked as invalid
3-pt smooth: 1 ☐ Add data for reverse direction travel
19-point smooth: 3
☐ Write data as Format 30 file
☐ Write data as Format 40 file 0 smooths
☐ Write data as Format 45 file
Smooth: 0
☐ Write data as Format 11 file
☑ Include speed data in file
☐ Write all GPS data as Format 20 file
☐ Write edited GPS data as Format 20 file
☐ Filter heading 1000 points
☐ Ignore earth rotation (for APA)
319942 Random seed (randomize if 0)
☐ Generate new random seed each time
☐ Use default file names
☐ Write Format 50 file for analysis and plotting
☐ time ☐ speed
☐ lat/lon ☐ accel
☐ altitude ☐ omega
☐ distance ☐ attitude
☐ flags
○ 0.01 ● 0.1 ○ 1 sec
☐ feet ☐ degrees
Status: Done reading Format 1x file for plotting

Figure 7. ENSCO MultiSim inertial sensor simulator.

For testing and for use with the simulator, we have recorded data for a variety of vehicles using the laboratory evaluation system from the Type 1 contract and the GINIUS IMS from the present contract. 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 or ENSCO 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. Additional GPS data was recorded after the improvement in quality due to the government's decision to remove selective availably from the GPS signal. More recently, inertial data has been recorded using the GINIUS sensors.

An example of a test using simulated data is shown in Figure 8. In this case, both sensor and GPS data are available in the simulated data and the GINIUS navigation and Kalman filter software correctly navigates the circuit, limited only by the accuracy of the GPS data. In the figure, the GPS data is hidden behind the almost identical Kalman filter output. This test used simulated GPS and inertial sensor data for a round trip on the Walt Disney World Railway. The track radius is 765 m (0.5 mi) with a circumference of approximately 5 km (3 mi). The trip was 21.5 minutes at speeds up to about 5 m/s (18 km/hr, 11 mph) and included stops of 4.5 and 5 minutes.

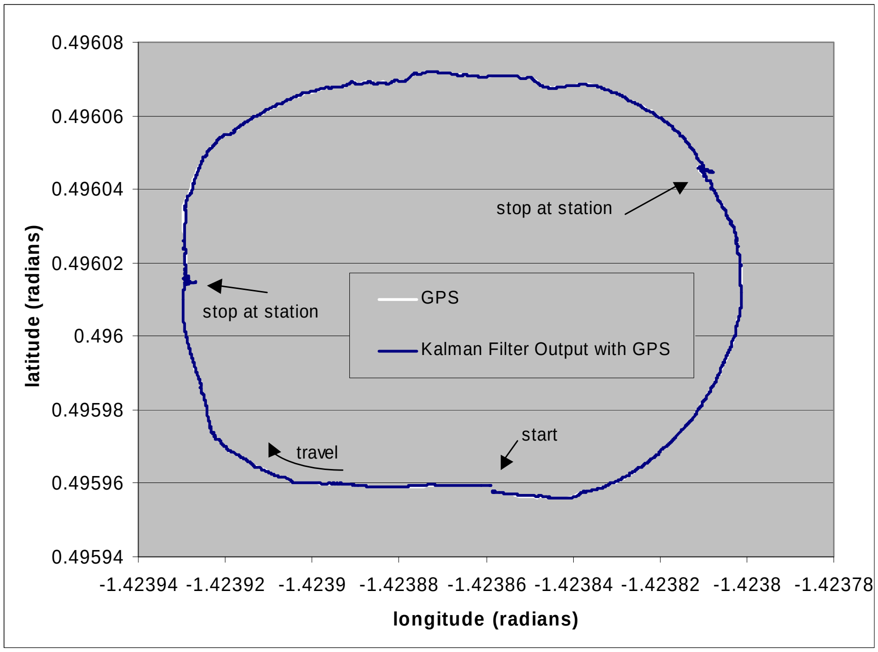
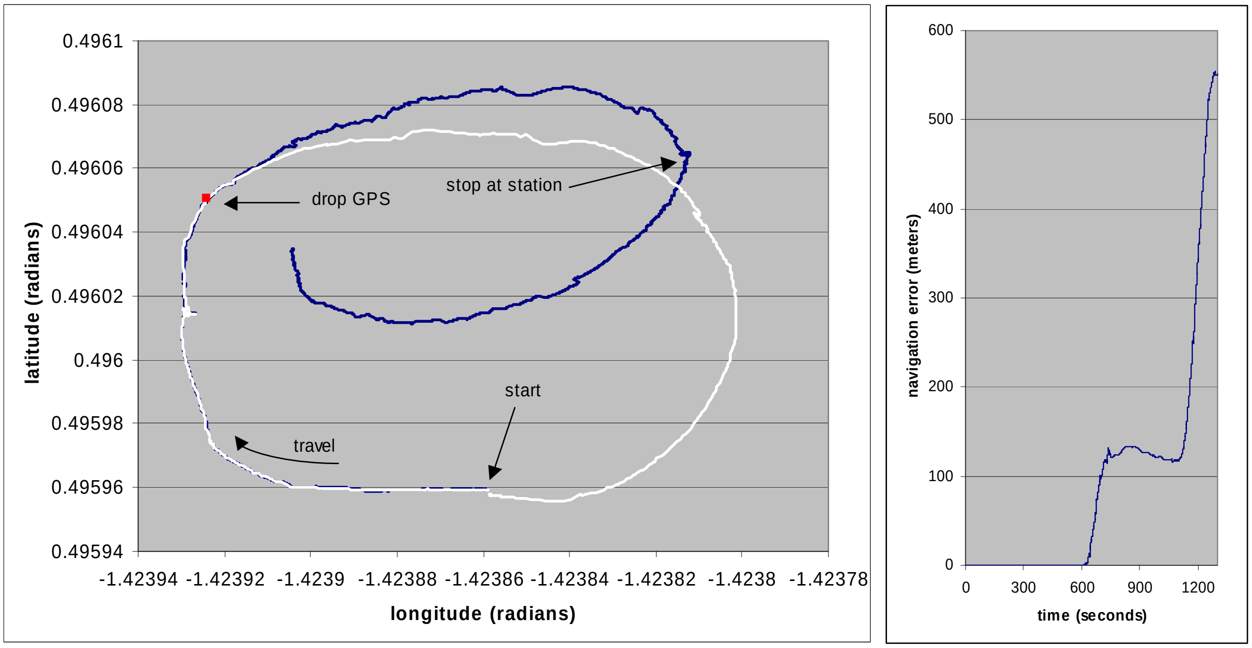


Figure 8. Test with simulated GPS and sensor data for navigation and Kalman filter software. The simulation is based on GPS position data recorded on the Walt Disney World Railway.

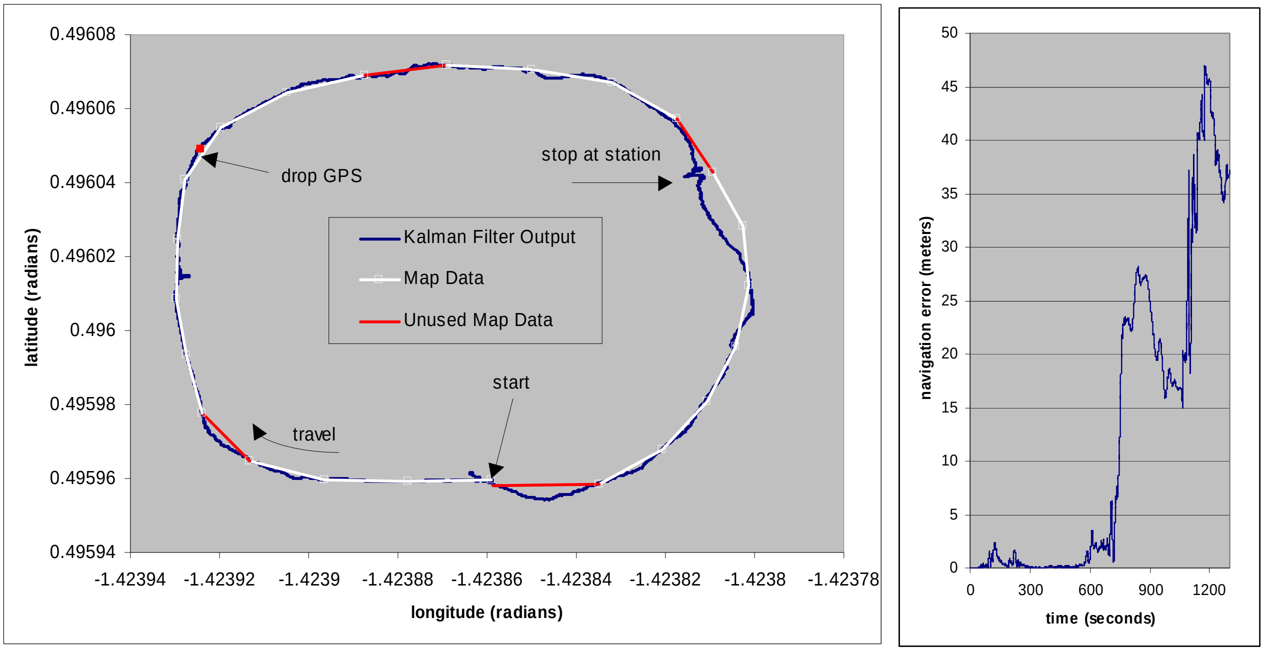
We tested the ability of the GINIUS system to navigate without GPS data by simulating the loss of GPS after 10 minutes of travel (including a stop at a station). The navigation results deviated from the actual track location, as seen in Figure 9a . During a 5-minute stop at the next station, the azimuth drifted significantly. The navigation error (in meters) for the simulation is shown in Figure 9b. The error exceeds 100 meters at the end of three minutes simulated travel to the station and increases to over 500 meters after leaving the station with an incorrect heading.



(a) (b)

Figure 9. Test using simulated loss of GPS. The rotation while stopped at the station has been eliminated by later filter enhancements that freeze azimuth and position when the speed of the locomotive is zero.

To compensate for the low accuracy of the simulated MEMS sensors, GINIUS was given the capability to make use of speed sensor data and map information.. The map information is a set of latitude-longitude points along the track, as could be obtained from the track databases maintained by many railroads. To test the new features, a simulation was generated in which GPS data was dropped after 10 minutes of travel and the remainder of the navigation was performed using inertial and speed data along with map information. Position errors in the GINIUS navigation solution were less than 50 meters, even after 11 minutes without GPS (6 minutes travel and a 5-minute stop). The resulting navigation path is shown in Figure 10a. The navigation error (in meters) for the simulation is shown in Figure 10b.



(a) (b)

Figure 10. Test with simulated sensor data for navigation and Kalman filter software using map and speed information. The simulation is based on GPS position data recorded on the Walt Disney World Railway.

As seen in Figure 10, there is still a drift in azimuth while the locomotive is stopped in the station. The navigation is corrected by the use of map data, but the there is a deviation from the track for a period of time after leaving the station. To prevent drift in azimuth and position while a locomotive is stopped, the Kalman filter has now been modified to freeze the azimuth and position under such circumstances.

5.8 CALIBRATION PROCEDURES

Calibration procedures for the GINIUS system have been developed and are documented in the ENSCO internal document *Inertial Sensor Assembly Factory Calibration*. The report presents recommended methods of calibrating the complement of accelerometers and gyros. By calibration, we mean the determination of the parameter values to be used to correct the sensor output for systematic errors.

There are three steps in the calibration. It is a relatively straightforward task to determine the bias, scale factor error, and mutual misalignment of the accelerometers. The calibration is performed by gathering data in a number of orientations of the sensor assembly and fitting the data to the accelerometer error model. The gravity sensed by a supported accelerometer in the laboratory is a strong enough signal to allow an accurate determination of the errors. The report gives a comprehensive description of the calibration procedure.

Calibrating the accelerometers of a cluster of inertial sensors is 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 because the accelerometer output itself establishes them. 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.

Determination of the gyro scale factor errors, misalignment with respect to the accelerometers and, in particular, bias errors is a more difficult undertaking. Gyros stabilized in the laboratory sense only earth rate, which is much too weak a signal to suffice, so it is necessary to apply controlled rotations to the assembly. Our method integrates the measurements from a 90-degree rotation to determine the scale factor for the gyro in the principle axis and the alignment for the other two gyros. The gyro biases are easily obtained from static measurements.

5.9 SENSOR SELECTION AND EVALUATION

We evaluated technology options for sensors a each stage of the project. The Analog Devices ADXL105 accelerometers were found to be the best available option for our application. Analog Devices also recommends the ADXL202 or ADXL210 accelerometers for low-cost applications. However, those sensors have a duty-cycle output rather than a voltage output. They have less accuracy than the ADXL105 and do not have an integrated temperature sensor or uncommitted amplifier. There is an evident industry trend toward simpler, cheaper MEMS accelerometers for applications such as automotive sensing. However, increased accuracy has not been a feature of these recent releases.

The ADXRS150 gyros, which we selected originally, still appear to be the best available choice. The ADXRS150's were previously scheduled to be available commercially in Summer 2001, but introduction was delayed several times. They became available in limited quantities in 2002 and are presently available as a standard product. We have three ADXRS150 samples for use in the GINIUS prototype system. The ADXRS150 is a 150 deg/sec angular rate sensor (gyroscope) on a single chip, complete with all of the required electronics. Two polysilicon sensing structures each contain a dither frame which is electrostatically driven to resonance. A rotation about the z-axis, normal to the plane of the chip, produces a Coriolis force which displaces the sensing structures perpendicular to the vibratory motion. This Coriolis motion is detected by a series of capacitive pickoff structures on the edges of the sensing structures. The resulting signal is amplified and demodulated to produce the rate signal output. The device has integrated, digitally controlled self-test feature that can be operated while the sensor is active. It includes a temperature sensor for temperature coefficient calibration, as well as a precision voltage reference.

The device has changed slightly from the original -- the package is now a 32-pin Ball Grid Array surface-mount package measuring 7 mm x 7 mm x 3 mm instead of the original dual inline package (DIP). Specifications are the same or better, and there is much more detailed technical information, including shock, vibration, and temperature compensation. The original estimated price in 2000 was $150 each in quantity of 100 pieces. The present quantity-100 price is $33, illustrating the dramatic price decrease that has been characteristic of MEMS devices.

5.10 ELECTRONICS AND PACKAGING DESIGN

We completed the electronics and packaging design and selected a computer system based on the IDAN System from Real Time Devices USA, Inc. The system includes a Pentium 300 MHz CPU, 20-GB hard drive, video and Ethernet interfaces, a GPS module, and a data acquisition system. There is a PCMCIA card controller for flash memory to be used to replace the hard drive when operating on a locomotive. The descriptions, specifications, and prices of the components chosen for the final design are presented in Table 2. A picture of the assembled system configured for GINIUS testing is shown in Figure 11. The computer includes a blank, double-height IDAN frame for mounting the sensor hardware within the assembled computer system. The data acquisition system includes external interfaces to allow optional connection to an external sensor system.

Vendor	Part No.	Description	Unit Cost
CPU Module			
RTD USA	IDAN-CMC16686GX300HR-64D	PC/104+ IDAN 686 Geode 300MHz Pentium Class MMX Enhanced Processor with 32MB RAM, 2 serial ports, 1 parallel port	$1,245.00
Non-Volatile Memory			
RTD USA	IDAN-CM6109HR-2D	Dual PCMCIA Card Controller	$695.00
Kingston		256MB Compact Flash	$140.00
Hard Drive option			
RTD USA	IDAN-CMT107D	20 GB Hard Drive	$695.00
Video			
RTD USA	IDAN-CM110HRS	SVGA video with flat panel support	$495.00
Networking			
RTD USA	IDAN-CM202S	NE2000 Ethernet with 10Base-2 coax, 10Base-T, and AUI interfaces	$437.00
Power Supply			
RTD USA	IDAN-HPWR104HRTX-75WS	75 Watt power supply	$545.00
VICOR	VI-J00	DC-DC Converter Module: 25-75W	$65.00
Enclosure			
RTD USA	IDAN-Base-BF	Base plate - with mounting flange	$87.00
RTD USA	IDAN-Cover-TH	Top cover with handle	$97.00
RTD USA	IDAN-Bolts-BB	Four bolts to assemble IDAN modules	$45.00
RTD USA	IDAN-Frame-DH	Blank double-height IDAN frame. Sold with IDAN cpuModules only.	$150.00
Cables			
RTD USA	IDAN-IFK-2	Cable kit	$595.00
Operating System			
RTLinux	RTLinux 3.0	Real-Time Linux Operating System	$150.00
Digital I/O			
RTD USA	IDAN-DM6430HR-1-68S	DM6430HR-1 HighRel 16-bit, 100 kHz 16 channel analog inputs, 1K FIFO, 16-Bit 200 kHz analog outputs and 16 digital I/O lines.	$895.00
GPS 12 Satellite Receiver			
RTD USA	IDAN-SK-GPS140HRS	GPS140HR NMEA-0183 Compatible GPS positioning board with 12 parallel-channel satellite receiver with differential GPS support. Direct interface through onboard 16C550 UART channel + active antenna	$845.00
		Total Cost	**$7,181.00**

Table 2. GINIUS Computer System Configuration and Pricing.

Figure 11. GINIUS computer system front and rear views.

5.11 TEST PLAN

A preliminary field test plan was developed. Because the locomotive test was not performed, the test plan does not include the specific information that would have been added once the exact schedule and other details were determined.

5.12 REAL-TIME SOFTWARE DEVELOPMENT

During the IDEA Type 1 project, non-real-time software was developed to implement the navigation and Kalman filter algorithms. The software successfully read inertial and GPS data from a file and produced navigation results. The results were validated with simulated inertial data by comparing the filter output with the source data for the simulation. Using ENSCO IR&D funding, the software was extended to include algorithms for speed-sensor data, map information, freezing of position and azimuth at zero speed, constraint of lateral motion, odometer calculations, and use of transponder data. The code was designed to run under either the DOS or Windows operating system.

The major software task of the present contract was to convert the existing non-real-time code to run in real time under RTLinux. We chose to code real-time software in C, while keeping the existing navigation and Kalman filtering algorithms in Fortran. We determined that the existing Fortran code could easily be ported to the Gnu Fortran 77 compiler, allowing us to use RTLinux as the execution platform. The Gnu compiler allows us to combine current Fortran modules with real-time C code. We converted the non-real-time code to compile on the Gnu Fortran compiler and successfully ran the compiled software. We developed interfaces between real-time C code and the existing Fortran routines. The software was developed as C-language real-time code in which incoming data was placed in a buffer which was then processed in real time by the Fortran code. During the time period when the remaining data and user interfaces were being developed, it became apparent from laboratory testing that the assembled sensor system would not have the needed accuracy. Earlier simulations based on manufacturer specifications had indicated that the sensors might be acceptable. However, the detailed sensor specifications needed for navigation applications were not available from the manufacturer and could only be determined by testing the assembled system. Testing indicated that navigation could not be achieved.

The C-language software modules are listed in Table 1, which gives the total lines of code, including internal documentation. The bufferdata routines perform the real-time data buffering, the kalmanfilter routines provide a data interface with the pre-existing Fortran code for navigation and Kalman filtering, and the preliminary gpsinput routines perform GPS data input. The table does not include the Fortran code, which was developed under the IDEA Type 1 contract and with ENSCO IR&D funding.

Program	Module	Lines
bufferdata	basicfuncs.c	90
bufferdata	display.c	145
bufferdata	get.c	263
bufferdata	initialize.c	119
bufferdata	main.c	305
bufferdata	record.c	143
bufferdata	terminate.c	21
bufferdata	write.c	54
bufferdata	bufrconsts.h	15
bufferdata	decbufrs.h	95
bufferdata	decfilptrs.h	16
bufferdata	defbufrs.h	95
bufferdata	deffilptrs.h	11
bufferdata	genconsts.h	39
kalmanfilter	display.c	147
kalmanfilter	main.c	346
kalmanfilter	terminate.c	23
gpsinput	main.c	204
gpsinput	nmeaparser.c	552
Totals	19 modules	2683 lines

Table 3. Software Modules.

5.13 PROTOTYPE ASSEMBLY AND TESTING

The GINIUS sensor system was assembled on two separate circuit boards to facilitate development and testing. The three Analog Devices ADXL105 accelerometers were mounted together on one of the boards. Each accelerometer had separate potentiometer adjustments for bias and scale factor. Cabling was chosen to have the same connector as supplied with the Analog Devices Accelerometer Evaluation Modules, Model ADXL150EM-3, used in the IDEA Type 1 project. The same cable configuration was also used for the laboratory sensor system in the Type 1 contract. This configuration allowed the accelerometer board to be plugged into the Type 1 laboratory system, replacing the existing accelerometers, or be connected separately to the data acquisition system.

The three Analog Devices ADXRS150 gyros were mounted on a separate circuit board. Each gyro was given the same cable connector as supplied with the Murata ENV-05 piezoelectric gyros used in the laboratory system for the Type 1 project, allowing the gyros to be interchanged for testing. The circuit boards were mounted in a case with a DB37 connector to allow a direct connection to the data acquisition system. The assembled system is shown in Figure 12 along with the enclosure used for testing.

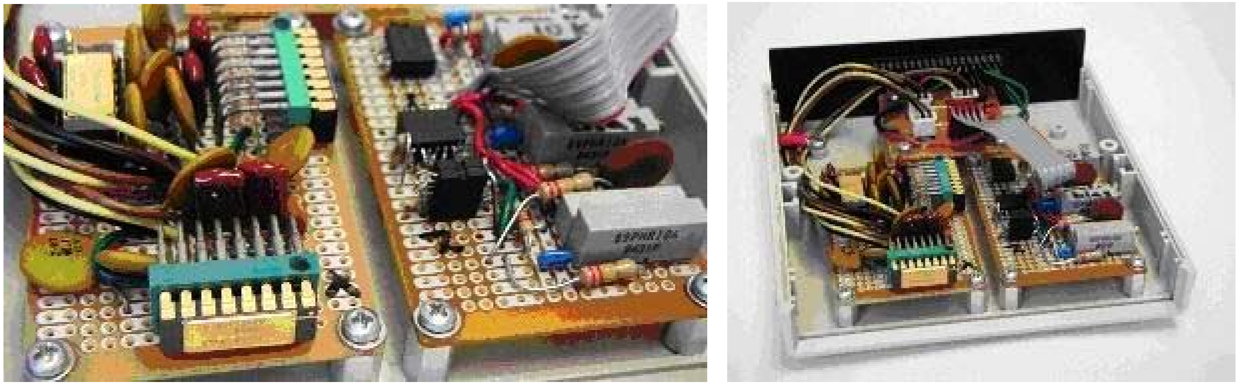


Figure 12. GINIUS prototype inertial measurement system and enclosure used for testing.

For the initial bench testing, the accelerometer board was connected to the laboratory sensor system from the IDEA Type 1 project. Measurements were performed with the unit mounted in various orientations to measure gravitational acceleration. Serious problems with drift and repeatability were observed in the early measurements. A comparison test using the original Type 1 project accelerometers provided similar results. The problems were found to be due to aging components of the original laboratory system, and were not due to the new accelerometer system. The remainder of the testing was performed without connection to the Type 1 laboratory system. The completed accelerometer and gyro boards were mounted in a case and placed on a surface or oriented on an index head (Figure 13). The index head provides a stable platform with adjustable elevation angle and a precision azimuth adjustment. Bias and scale factor parameters were determined for the accelerometers by measuring the gravitational acceleration in different orientations. The gyro scale factors were determined by integrating the measurements from a 90-degree rotation and the gyro biases were obtained from the average of a set of static measurements. A program was written to automate the process of sensor calibration by recording a series of measurements and calculating the required parameters.

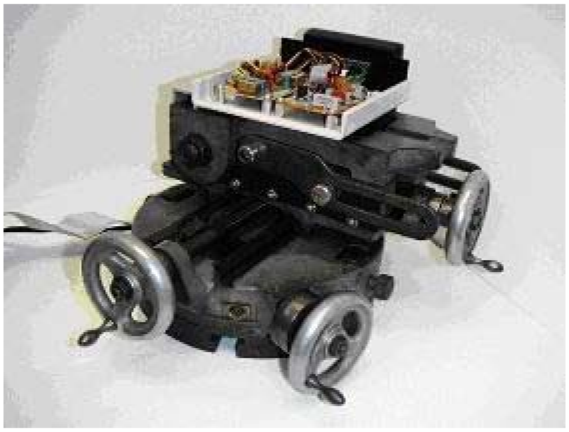
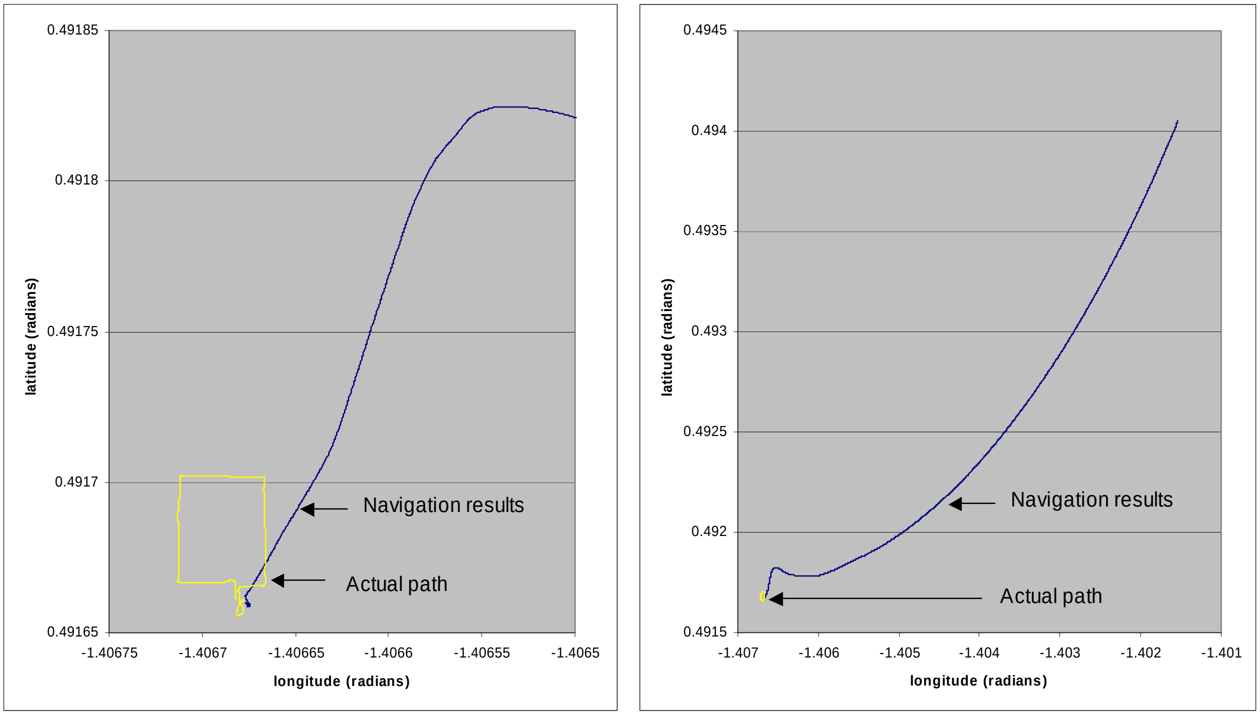


Figure 13. GINIUS IMS on index head for testing.

To determine the ability of the assembled sensor system to perform navigation, we used an automobile to record a trip driving around a city block. The car remained motionless for the first two minutes to allow initialization of the Kalman filter. The raw data was converted into the format used by our GINIUS Kalman filter and navigation system. A fixed position was provided in the data for the first two minutes, and then no additional position information was presented to the filter. This procedure has the effect of determining what navigation could be performed in an operational real-time system if the GPS signal were unavailable after the end of the 2-minute initialization period. We then processed the data with the non-real-time version of the GINIUS system. Unfortunately, we have been unable to obtain any valid navigation output using this procedure. Our results for the estimated navigation path are shown in Figure 14. The light-colored block is a map of the actual path taken by the automobile, using earlier recorded GPS position data. The dark line is the navigation solution. The navigation is in error by over 500 meters at 60 seconds, over 1200 meters after 90 seconds (which is the portion of the path shown in Figure 14a) and off by 32000 meters (32 km) at the end of the full 290-second path illustrated in Figure 14b.



(a) First 90 seconds of path after start of motion (b) Full path showing 290 seconds after start of motion

Figure 14. Result of attempted navigation around a city block using an automobile.

We also performed measurements and analysis to determine gyro sensitivity. For the most sensitive test, the GINIUS sensor package was left stationary for 50 minutes to determine how accurately earth rate (the rotation rate of the earth) could be determined. The measurement of earth rate is essential to any accurate inertial navigation system, since it is the only method for measuring an absolute azimuth during initialization. The 50 minutes of recorded data was processed by the GINIUS Kalman filter and navigation software and no earth rate was detected. The output was a gradual drift of the azimuth with no indication that earth rate had any influence. (In earlier filter testing, earth rate had been easily detected using simulated data corresponding to more accurate sensors.) Analysis of the signal indicated that the noise level appeared to be at least 10 times greater than the signal level expected to be produced by rotation of the earth. We conclude that the MEMS gyros as tested are not sufficiently accurate for azimuth initialization.

To determine how the system would perform with more accurate sensors, we also tested the navigation and Kalman filter software using recorded data from a Honeywell HG1700 IMS (Model HG1700AG17). The ENSCO APA Division recently obtained the HG1700 and was able to begin recording data in January 2004 at their location in Greensboro, NC. We used data recorded in an automobile for a closed path that returned to the starting point 3 minutes later. The navigation error after 3 minutes was 45 meters. The resulting calculated path is shown in Figure 15. No GPS data was taken, so that the actual path is not available for plotting and the only accurate error estimate is the 45-meter error after completing a closed loop. (The ENSCO APA Division performed a similar evaluation using the same data with a different non-real-time version of a navigation system and found a similar navigation error.) Since current PTC specifications require accuracy to within 10 feet with 99% confidence, it does not appear that even the HG1700 accuracy would be sufficient for locomotive navigation if used alone. Our experience with simulated data in the past (as discussed in Section 5.7) suggests that with sufficient tuning of the filter, the use of a detailed map database, accurate wheel tachometer data, and DGPS input, we can expect navigation with the HG1700 to approach the accuracy needed for the PTC specification. However, the HG1700 IMS does not use MEMS technology and would not meet the goal of our project, which was to base a navigation system on inexpensive MEMS sensors. When the earlier Type 1 IDEA project began, MEMS gyros had been developed by Draper Laboratories that were expected to soon be commercially available. It now appears that these sensors form the basis of the new Honeywell HG1900 IMS. However, the HG1900 has lower accuracy than the HG1700, and the present cost of the HG1900 is approximately $30,000, which is far out of reach for this project. We expect the price to fall, but not into the “low-cost sensor” range in the near future.

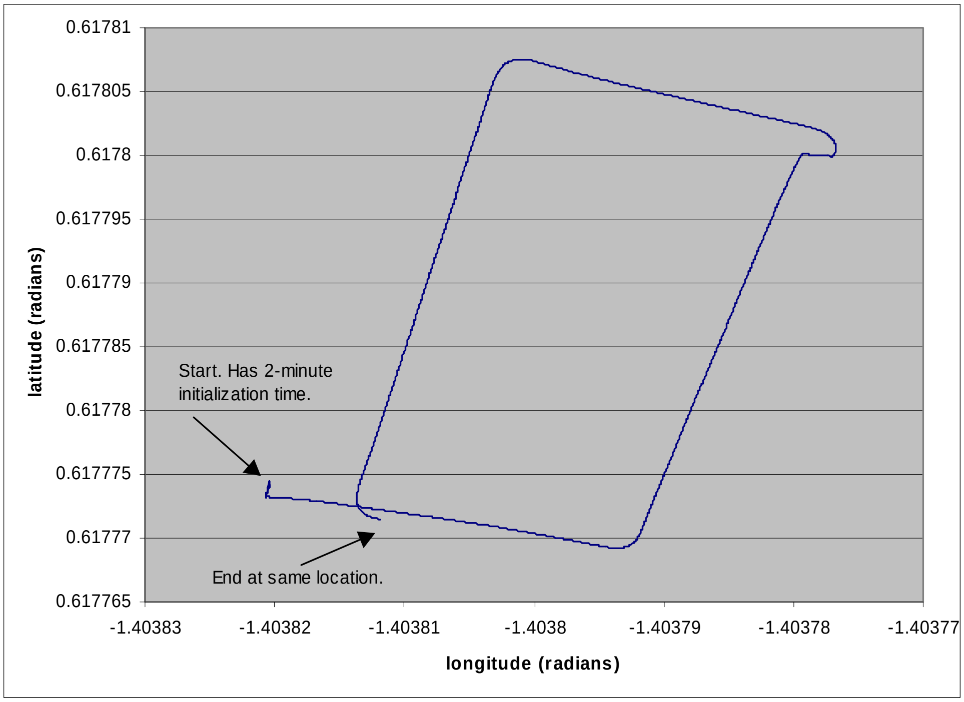


Figure 15. Result of navigation around a city block using an automobile with a Honeywell HG1700 IMS.

The goal of this project was to develop an inertial navigation system capable of meeting PTC requirements, which include a position accuracy requirement of 10 feet or better with 99% confidence. For locations where a satisfactory GPS signal is available, this requirement can be met with current navigation systems that use accurate DGPS receivers. It can also be met by the GINIUS system developed by the current project if DGPS is used, since the navigation output closely matches the GPS input data. However, when the GPS signal is lost, as can occur due to buildings, tunnels, foliage, or terrain, additional navigation capabilities are needed to determine location until GPS again becomes available. The question now becomes: How far can the locomotive proceed before the navigation errors exceed the levels specified in the PTC requirements? The position error of 45 meters (over 145 feet) after 3 minutes, shown in Figure 15, is 15 times the error allowed by PTC requirements. Hence, even with the accurate HG1700 IMS, it appears necessary to use other navigation techniques, including use of speed data and map information. From our experience with simulated results of the type shown in Figure 10, it appears likely that PTC requirements could be met using such a combination of data. As an independent viewpoint, the PTC specifications (Ref. 3, page 49) state sensor accuracies that are in the same range as the HG1700, implying that it should be sufficiently accurate. It does not appear that the sensor accuracy could be reduced significantly and still achieve PTC accuracy. In contrast, from the results of the navigation using MEMS sensors, as depicted in Figure 14, the inertial navigation is of little value in comparison to speed and map information, which would be more accurate.

It is difficult to estimate how much MEMS sensor accuracy would have to increase in order that useful navigation results could be obtained, since the MEMS sensor specification sheets provide parameters that are more appropriate for current uses (such as automotive applications) than for navigation. Unfortunately, our best indication of the performance of the MEMS sensors comes from actual output of the navigation system using MEMS sensors which, in our case, did not yield useful navigation. Throughout most of the project, we had no direct data that could conclusively determine the accuracy of the resulting system. Near the end of the project, we had available the two new sources of information: measured data from the Honeywell HG1700 IMS and the completed GINIUS sensor system. From these sources, we conclude that a MEMS-based navigation system would either be prohibitively expensive (using a commercial MEMS HG1900 IMS at present prices -- about $30K) or would not have the accuracy for navigation (based on our present prototype sensor system). We believe that accuracy on the same order of magnitude as the HG1700 is needed for successful locomotive navigation.

6. PLANS FOR IMPLEMENTATION

Even though the end product of this effort is not ready for commercialization in its present form, future improvements in sensor technology could allow completion of this project as originally envisioned. The question is not *if* suitable MEMS sensors will appear, but *when*. The appearance of the $30K Honeywell HG1900, based on MEMS gyros developed by Draper Laboratories, shows that practical MEMS gyros exist, just not yet at practical prices. Industry motivation to improve MEMS accelerometer accuracy have been hampered by the high demand by the automotive industry for very low-cost accelerometers. Accelerometer accuracy has been determined by automotive applications and industry competition has been for the lowest cost and for improvements in other characteristics, such as temperature stability.

The basic assumption made for commercializing the GINIUS has been 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 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 GINIUS 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.

A commercialization plan for the GINIUS navigation system was presented in the final report for the Type 1 IDEA project. Since that time, there have been many improvements that should make the present system even more practical:

- The original Type 1 project recommended the use of sets of accelerometers to replace gyros. The accuracy of such a process was found to be adequate for detecting the movement of a locomotive from one track to a parallel track, but such a system is not accurate enough for navigation. The present GINIUS system uses MEMS gyros for improved accuracy.
- The Type 1 report recommended using a central computer with four or more sensor modules distributed over the length of a locomotive and connected by cables to the central processor. The present system is self-contained except for an external GPS antenna.
- Calibration was expected to be extraordinarily difficult for sensor modules mounted at distant locations in a locomotive. The conventional calibration procedure of tilting all sensors at once to determine the relative orientation is impractical, since a locomotive cannot be expected to be inverted or tilted on its side. The present system can be calibrated as a unit before installation.
- Flexing of a locomotive was considered to be a possible source of error for the original system, since sensor systems in different locations would then have different time-dependent relative orientations. The present centralized system eliminates that problem.
- Several computer choices were considered for the original system. We consider the present choice to be the best for prototype development and to use as a basis for later commercialization.
- The navigation and Kalman filtering algorithms and software are greatly improved over the Type 1 versions. Many of the present features and enhancements were not considered in the Type 1 design, but were added. These improvements include the ability to freeze position and orientation when the locomotive’s motion has stopped and a method of constraining predictions of lateral motion.

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. ENSCO plans to combine its IMS and GPS efforts in order to develop integrated GPS Inertial Navigation Systems.

Another promising application of the GINIUS 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 INSs, 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 INSs, 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.

Our present goal is to produce a $2000-3000 GINIUS that improves the accuracy of DGPS navigation and allows navigation in areas without adequate DGPS signals. Our long-term goal is to use expected future technology to produce an under-$2000 GINIUS that provides the performance of a 1-deg/hr conventional IMS.

ENSCO intends to market the GINIUS 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.

A recent ENSCO 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.

7. CONCLUSIONS

This project investigated the concept of using low-cost accelerometers and gyros to replace the more expensive sensors used for conventional inertial systems. Navigation and Kalman filtering software was developed with innovative features to improve the performance of the low-cost sensors for rail applications. The algorithms and software were successfully tested with simulated data and verified by the use of recorded data. An inertial measurement system using MEMS accelerometers and gyros was developed and tested. However, the accuracy of the inertial system was too low for it to be used for successful navigation. A comparison of present low-cost MEMS sensors versus conventional sensors showed that there is still a gap that may be too large to bridge with current technology.

The primary obstacle to the construction of a successful low-cost navigation system has been the lack of accurate sensors. Although MEMS sensor technology was increasing rapidly before the start of the IDEA projects, more recent advances in MEMS sensor accuracy have slowed dramatically. Technologies such as tunneling-tip sensors, that had appeared to be promising at the start of the project, have failed to materialize. The accuracy of low-cost MEMS accelerometers has not increased appreciably since the start of the original Type 1 contract. When the earlier IDEA project began, MEMS gyros had been developed by Draper Laboratories that were expected to soon be commercially available, perhaps within the year. Only in the past year have these sensors been introduced as the basis of the new Honeywell HG1900 IMS. However, the present cost of the HG1900 is approximately $30,000, which is far out of reach for this project. We expect the price to fall, but these sensors are unlikely to be considered to be "low-cost" in the near future. From recent tests on our sensor system and comparison to a (non-MEMS) commercial HG1700 IMS with accuracy similar to the HG1900, it does not appear likely that the present inexpensive MEMS sensors have the accuracy needed for precision navigation. Our conclusion is that a MEMS-based navigation system would either be prohibitively expensive (using a commercial MEMS HG1900 IMS at present prices) or would not have the accuracy for navigation (based on our present prototype sensor system).

Our recommendation is that the development of a low-cost inertial navigation system should be a goal to be pursued once MEMS sensor technology improves. We still believe that in the future, low-cost MEMS sensors will be available that can provide the accuracy needed for navigation. The cost of navigation systems based on MEMS technology has the potential to show the same decreases in cost and improvements in performance that were seen in the electronics industry with the development of transistor and integrated circuit technology. The availability of low-cost navigation systems will open doors to many new applications, both in the rail industry and in many other areas.

8. INVESTIGATOR PROFILE

8.1 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 currently providing independent support to the space program under the SPEV (System Performance Evaluation and Verifications) contract and he has been 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 performed 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.

8.2 OTHER KEY PERSONNEL

In his work as Principal Investigator, Dr. Riewe was supported by ENSCO Staff Engineer Mr. Brian E. Mee, Senior Software Engineer Ms. Juli Miller, and independent consultant Mr. Harry Gaines. Mr. Manuel Perez, began his support as an ENSCO Staff Scientist and continued as an independent consultant after his retirement in September 2002.

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. Mr. Perez retired from ENSCO in September 2002 and continued supporting the IDEA program as an independent consultant.

Brian Mee, ENSCO Staff Engineer, 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.

Juli Miller, ENSCO Senior Software Engineer, has B.S. degree in Mathematics from Florida Atlantic University. She has 12 years experience in software engineering, including recent real-time programming experience.

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.

9. ACRONYM LIST

This list is a compilation of acronyms used in this report.

APA	Advanced Products and Applications (ENSCO Division)
ASE	Aerospace Sciences and Engineering (ENSCO Division)
COTS	Commercial Off-The-Shelf
DGPS	Differential GPS
DIP	Dual Inline Package
FCC	Federal Communications Commission
FRA	Federal Railroad Administration
GINIUS	GPS Inertial Navigation Instrument Universal System
GRMS	Gage Restraint Measurement System
GPS	Global Positioning System
IDEA	Innovations Deserving Exploratory Analysis
IMS	Inertial Measurement System
INS	Inertial Navigation System
IR&D	Internal Research and Development
MEMS	MicroElectroMechanical Systems
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NRC	National Research Council
PTC	Positive Train Control
PTS	Positive Train Separation
RMA	Reliability, Maintainability, and Availability
SSAD	Subsystem Architecture Description
TRB	Transportation Research Board

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