INERTIAL SENSORS CAPABILITIES

1.0 LORD CORPORATION

1.1 LORD's Inertial Sensors Group Mission

LORD's Inertial Sensors Group has comprehensive capabilities in all aspects of Inertial Sensor design and manufacturing. We specialize in utilizing the latest, best performing MEMS sensors (accelerometers and gyros) to create products. We are integrators. We do not manufacture the MEMS sensors themselves, instead we integrate them into systems which satisfy our industrial and aerospace customer's needs.

LORD maintains a standard inertial sensor product line. In many cases, these sensors are suitable, off-the-shelf, for our customer's applications. In other cases, our customer's applications require something non-standard. In those cases, we are able to provide custom solutions which directly address the application's special needs.

Inertial sensor technology, especially that based on MEMS concepts, evolves very quickly. LORD strives to be a leader in understanding this evolution, and implementing the highest value components into products for our customers.

1.2 Overview of LORD Corporation

LORD Corporation is a global, diversified, technology-based company specializing in the design, manufacture and marketing of products for Aerospace, Defense and Industrial customers. LORD has 10 domestic and 12 international manufacturing facilities. Worldwide, LORD has more than 90 strategically located sales and support centers.

LORD Corporation is a privately held company with annual sales in excess of $850 million and total employment of approximately 3,000 worldwide. Approximately 45% of LORD employees have technical degrees.

World Headquarters: Cary, North Carolina USA

History: Founded in 1924 by Hugh C. Lord

Markets Served:
Aerospace and Defense (Commercial Aircraft, Military Aircraft, Missile Systems, Tanks and Artillery)
Transportation (Automotive, Rail, Truck/Bus, Agriculture, Recreational and Marine)
Manufacturing (Industrial Assembly, Process Industries)
Construction (Flooring, Civil Engineering, Off-Highway Vehicles)
Electronics (Chip Assembly, Component Assembly)

Technologies:
- Sensing Systems
- Balancing
- Active Vibration Control
- Elastomeric Vibration Isolation and Damping
- Elastomer Bonding and Coating
- Structural Bonding
- Magneto-Rheological (MR)
- Fluid Vibration Isolation and Damping
- Corrosion Control Coating
- UV-Cured Coatings
- Electronic Thermal Management
- Electronic Device Protection

1.3 History of Inertial Sensing at LORD

LORD brought Inertial Sensing expertise in-house in 2012 by acquiring MicroStrain Inc.

MicroStrain first began designing and manufacturing MEMS based inertial sensor systems in 1998. At that time, low cost, reliable MEMS accelerometers had become available as a result of their widespread use in the automotive industry for airbag deployment. These accelerometers provided the core of MicroStrain's first Inertial Sensor product, the 3DM. They were capable of making 2 axis attitude measurements (Pitch and Roll) in static conditions. The addition of a triaxial magnetometer provided a means to additionally measure Magnetic Heading.

In 2001, MicroStrain began to incorporate MEMS angular rate sensors (gyros) into its 3DM-G series of Inertial Sensors. This provided full Inertial Measurement Unit (IMU) capability (3 axes of acceleration and 3 axes of angular rate). The 3DM-G was one of the first commercially available devices in its class.

In 2003, the first high performance MEMS angular rate sensors designed for the automotive industry became available. These provided a significant improvement in performance. MicroStrain incorporated these into its 3DM-GX1 product. This was the first truly industrial grade IMU to become available for less than $2000. It also included an early Kalman filter which provided attitude and heading measurements under dynamic conditions.

Since that time, MicroStrain has continued to upgrade its product offerings, increasing the performance and functionality. The 3DM-GX3 product added a full GPS/INS navigation Kalman filter, providing position and velocity estimates in addition to attitude. The 3DM-RQ1 was MicroStrain's first Tactical Grade Inertial Sensor specifically designed for aerospace applications. It is currently being used in a new generation of antenna pointing systems designed to deliver high speed internet services to the passengers on commercial aircraft.

MicroStrain was acquired by LORD Corporation, in 2012, and formed the first segment of LORD's Sensing Systems business unit.

INERTIAL SENSORS CAPABILITIES

The figures below illustrate several of LORD's most recent Inertial Sensor products.

Figure 1 3DM-GX4-25. This highly miniaturized sensor provides Industrial grade Attitude outputs.

Figure 2 3DM-RQ1. This product provides a tactical grade GPS aided navigation solution (position, velocity and attitude) in a fully aerospace rated package.

Figure 3 3DM-GQ4. This product provides tactical grade GPS aided navigation solution in product suitable for industrial customers.

2.0 INERTIAL SENSORS CAPABILITIES

The Inertial Sensors Group includes a world-class Inertial Sensor Design Team. This group is located in LORD's Williston, VT office, formerly MicroStrain Inc. The core design team includes experts with over 100 total years of experience. Their key skillsets and capabilities are described in the sections below.

2.1 System Architecture

Successful Inertial Sensor design always begins with careful consideration of the System Architecture. LORD MicroStrain has developed a high level of expertise in this critical area. The architecture defines the capabilities of each of the major elements in the system, and how they interact. Wise choices made at this level can have important impacts on the capabilities of the final system, its cost, manufacturability, and the useful lifespan of the resulting product line. A well designed system architecture results in a product which can be readily upgraded in the future or adapted to changing requirements, while still retaining maximum compatibility with previous and future systems

For example, many of LORD's current products, including the 3DM-GQ4 and 3DM-RQ1, utilize a dual-microprocessor design. The IMU processor handles the sensor data acquisition, as well as temperature compensation and all other aspects of applying calibration coefficients. Its output is the acceleration and angular rate vectors expressed in physical units. This data is then communicated to the NAV processor over a high speed serial bus. The NAV processor implements that Kalman filter which is responsible for estimating the higher level outputs such as Attitude, Position and Velocity. The NAV processor may also manage inputs from auxiliary sensors such as a GPS receiver, magnetometer, and pressure sensor. The slightly higher hardware complexity and cost of the dual processor architecture is outweighed by the significantly advantages achieved in segregating the major embedded software functions.

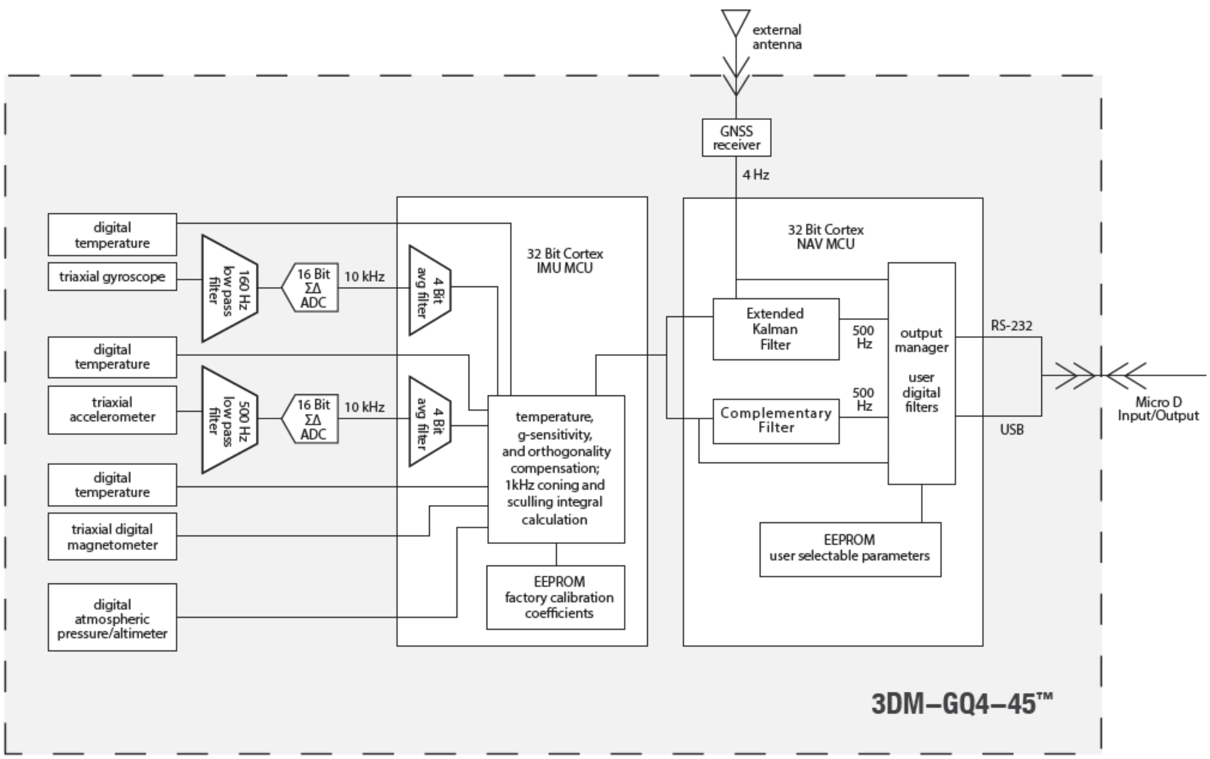

Figure 4 Block diagram illustrating dual processor system architecture

2.1 Kalman filtering

Kalman filtering is a powerful mathematical technique by which measurements from multiple sensors are combined in an optimal way in order to estimate quantities of interest. For inertial sensor systems, the outputs of the filter typically include position, velocity, attitude, and heading. The inputs to the filter include accelerometer and angular rate sensor measurements, and may include additional measurements from any number of aiding sensors: global navigation satellite system (GNSS) receivers, magnetometers, wheel speed sensors, barometric pressure sensors, etc. Note that not all of the outputs are directly measured by any of the input sensors – for example, no individual sensor is capable of measuring attitude. The Kalman filter incorporates a system model which relates the inputs to outputs as a function of time, and weights each sensor measurement according to its level of sensor noise to produce an optimal estimate of the output variables.

LORD has deep expertise in Kalman filter design and implementation. All of LORD's current inertial sensor systems include on-board Kalman filters operating in the NAV processor. The most advanced of these is a 25 state Kalman filter which combines three-axis accelerometer and angular rate sensors with a high performance GPS receiver, a three-axis magnetometer, and a barometric pressure sensor to provide highly accurate estimates of position, velocity, attitude, and heading.

LORD continually works to improve the performance of its filter designs, and to add functionality. LORD offers custom Kalman filter design capabilities to its customers. Customer applications frequently involve unique operating conditions, or the availability of unusual aiding sensors. In these cases, LORD has the capability to adapt its existing Kalman Filter designs to optimally utilize this unique information.

2.2 Modeling and Filter design

Modeling provides the ability to evaluate the performance of a proposed system, or some aspect of it, in the virtual domain. With LORD's modeling capabilities, scenarios can be run involving different sensor combinations and operating conditions to evaluate the performance of a particular filter design for any application. This toolset ensures that each application gets tailored performance from our inertial sensor systems.

2.2.1 Simulation

LORD has assembled a full set of tools for simulating the performance of an Inertial System including:

- **Trajectory Generator:** This software tool can be used to generate a trajectory corresponding to target applications. The trajectory is the complete (simulated) time history of the motions that the Inertial Sensor would be exposed to in that application. For example, the trajectory could be the path (including position, speed, acceleration, attitude, etc.) of an aircraft taking off from an airport, and flying a designated flight pattern.

- **Sensor Simulation:** A number of software tools can be used to generate simulated inertial and aiding sensor measurements based on the given trajectory.

- **Kalman Filter Simulator**: This software toolset provides a means to evaluate a candidate Kalman Filter design, using as its input either simulated sensor outputs or recorded data from real field tests. The Kalman Filter output can then be directly compared to the simulated trajectory (or truth data from a reference, if available, in the case of a field test) in order to assess the anticipated system performance.

2.2.2 Hardware-In-The-Loop

LORD has a full set of Hardware-in-the-Loop (HITL) tools. HITL is a general capability whereby certain aspects of simulation are combined with testing of actual candidate Inertial System hardware. The purpose is to evaluate the real-world aspects of the actual hardware in a manner that allows for direct comparison with a controlled input.

- **GPS Signal Simulator:** This hardware system can generate radio frequency signals that mimic real GPS radio frequency signals for a given trajectory. It can include important limiting effects like multipath interference and atmospheric distortion. These signals can be delivered directly to a GPS receiver.

- **Inertial Sensor Signal Simulator:** These software tools provide a means to take a set of simulated inertial sensor data, and "play" it directly into an actual inertial sensor system. This data essentially replaces the outputs of the actual sensors on the system. This executes in real time so that the performance of the complete inertial system (including its Kalman Filter) can be assessed.

2.2.3 Field test unit

LORD has an integrated field test unit that allows for rapid evaluation of candidate sensor systems for many proposed customer applications. A compact package houses LORD inertial products mounted alongside a high-grade GPS-INS reference, with optional dual-antenna GPS inputs. Power and data-logging capabilities are included onboard. This unit minimizes complexity and setup time for field tests. In addition to rapid product evaluation in the field, recorded test data can be used by our hardware-in-the-loop and Kalman filter simulation tools to customize filter performance.

During the field test (for example, driving in a car, boat or aircraft), both the reference system, and the inertial sensor under test are exposed to the same motions and conditions. Therefore, their outputs are directly comparable. This allows for identification of subtle errors that can occur in the system under test when operated in a real world application.

Figure 5 Photograph of GPS-INS reference unit (left) and typical Inertial Sensor under test (right).

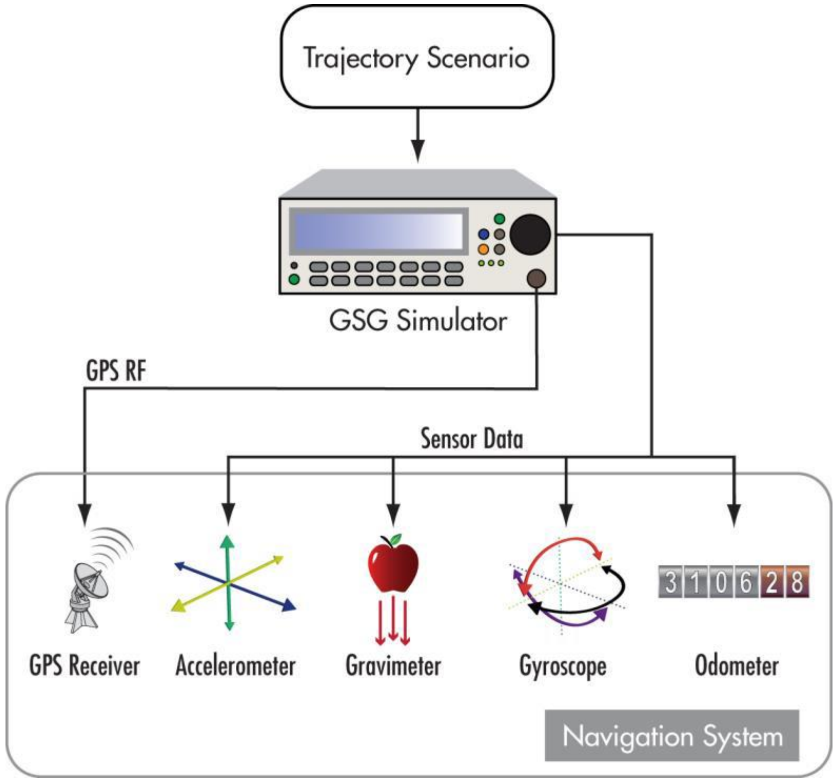

Figure 6 Illustration of modeling capabilities

2.3 Hardware Design

LORD has developed extensive expertise in all aspects of hardware design for its Inertial Sensor Products. High-precision analog signal acquisition is a core strength of the hardware design team. Professional toolsets are utilized for schematic capture and PC board design. Typically, miniaturization of the overall system is a high priority. High density PC board design techniques (including stacked microvias, chip scale packaging, etc.) are often used to achieve this goal. Designs are optimized to meet stringent EMI/EMC requirements, and "design-for-test" features are generally employed to improve quality and manufacturability.

LORD offers the capability to customize its sensor designs for those applications which require special configurations or functionality. In many cases, this can be accomplished in a very cost effective manner since existing designs can often be adapted to new purposes with relatively little engineering effort.

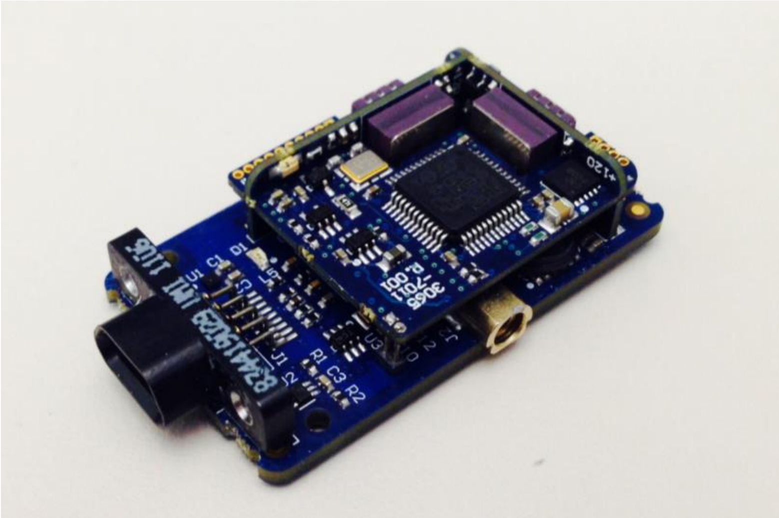

Figure 7 Example of high density PC board design

2.4 Embedded Software

LORD utilizes best practices for code design and development of its embedded software. Code frameworks are object oriented and developed using C++. The code kernel is time-deterministic ensuring reliable and monotonic sensor sampling. Code models are verified using hardware-in-the-loop (HITL) testing. The software application programming interfaces (APIs) are tested using automated test scripts with 100% API coverage. All source code and communication protocols (DCPs) are under document control using Subversion SCC. Compiled binaries are under strict version control via component BOMs in our enterprise PLM system.

LORD has considerable experience in the implementation of sophisticated algorithms such as Kalman Filters in embedded systems. We have combined that with a communications protocol (MIP™ Protocol) tailored specifically for wide, multi-rate data streams that are typical of outputs from Kalman filters and inertial sensors in general. This has allowed us to design powerful sensor architectures with multiple specialized processor cores running in parallel.

LORD is able to customize its embedded software for specialized applications. The object oriented approach generally allows for the reuse of the majority of code in any new platform.

2.5 User Interface Software

LORD utilizes LabVIEW, MatLab, Python, and C++ for development of desktop user software, test tools, calibration tools, and software development kits (SDKs). In addition, LORD MicroStrain's inertial products are integrated with SensorCloud™ and SensorConnect™ applications, enabling users to easily share, manipulate, and post-process massive amounts of inertial and navigation data.

2.6 Manufacturing

LORD generally utilizes a contract manufacturer (CM) to carry out manufacturing of the PC boards for its Inertial Sensor products. In some cases, LORD will then carry out final assembly of the product. In other cases, the CM will build the final assembly. In all cases, LORD perform the critical calibration and final testing on each of its products.

LORD, and its CM are both ISO 9001 certified.

2.7 Calibration

LORD has extensive expertise and facilities for use in carrying out calibration of its inertial sensors. Every inertial sensor is comprehensively calibrated and tested prior to shipping. The calibration is carried out over the sensor's full temperature range using custom designed and built calibration infrastructure. All calibration is fully automated, requiring minimal operator intervention. Each calibration station has a throughput of 5,000 to 10,000 sensors/year, depending on the sensor's size.

Typical calibration algorithms implement compensation for the following factors:

- Scale Factor over the full temperature range
- Offset over the full temperature range
- Non-Linearity
- Misalignment
- Gyro G-Sensitivity
- Finite Size Effect

Figure 8 Fully automated calibration system including environmental chamber to applying full temperature range.

2.8 Functional Testing

In addition to calibration, LORD carries out a comprehensive suite of functional tests on every inertial sensor shipped. This ensures a high level of quality. A custom functional test rack has been developed which is capable to carrying out a large range of tests in a fully automated manner. Examples of tests that are carried out include: power consumption, sensor noise, voltages at test points, GPS receiver functionality, electrical isolation, and many more.

Figure 9 Functional Test Rack used to test all inertial sensors

2.9 Qualification Testing

At many points in the design and verification cycle it is necessary to carry out more comprehensive testing on all aspects of the sensor's performance. LORD has capabilities to carry out much of this testing in-house including:

- Operating Temperature
- Altitude
- Vibration
- Crash Acceleration
- Highly Accelerated Life Testing
- Humidity
- Electro-Static Discharge
- Mechanical Shock

In other cases, LORD works with local laboratories to carry out certified testing which cannot be performed in-house. Typically, these include:

- Electro-magnetic Interference
- Electro-magnetic susceptibility
- Lighting-induced transients