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TITLE

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97-621

Motion Compensation Study

Task One Report

Task 1 Contract #0405V.W7714-6-0010

January 16,1997

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Work Performed for the Defence Research Establishment Ottawa

Contract Scientific Authority: W.J.L. Read

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Task One Final Report

Motion Compensation Study January 16, 1997

1. Introduction

Tactical Technologies has been contracted by DREO to investigate motion sensors which could be used to compensate for platform motion during ESM experiments (Contract No. 0405V.W7714-6-0010). This report summarizes the findings of Task 1 of that investigation, which resulted in a number of potentially suitable sensors having been identified.

Most of the information contained in this report is based on product literature from the various manufacturers, on telephone conversations with manufacturers' representatives, and on discussions with staff in the Navigation Group at DREO. In particular, TTI would like to acknowledge the support provided to us by Mike Vinnins from the Navigation Group.

2. Study Objective

In the near future experiments will be carried out by DREO using an ESM receiver system onboard an aircraft or a ship. In these experiments it may be necessary to compensate for platform motion in order to obtain the required accuracy of direction-of-arrival estimates. Either mechanical or electronic compensation techniques can be employed to correct platform motion induced errors, however, only electronic motion compensation techniques are being considered in this project since the required equipment can be made simpler, smaller and at less cost than for a comparable mechanical system.

The purpose of this contract is to investigate the application of antenna motion compensation techniques to minimize ESM direction-of-arrival errors due to platform motion. This investigation will focus on two different approaches. The first approach utilizes commercial off-the-shelf components (COTS) to provide information on the attitude (roll, pitch) and heading (yaw) of the ESM receive antenna array to the ESM system. The second approach relies on obtaining the requisite attitude and heading information from the platform navigation system. In either case the information supplied to the ESM system must be accurate, available when required, and provided in a useable format.

For the first approach using COTS equipment, TTI collected and evaluated information on inertial reference measuring systems and their associated motion sensor technologies.

3. Glossary

The following is a list of common abbreviations used to describe inertial systems and sensors. These terms were frequently encountered during the course of this study.

AHRS: Attitude and Heading Reference System

FOG: Fiber Optic Gyro

GPS: Global Positioning System

IMU: Inertial Measurement Unit

INS: Inertial Navigation System

RLG: Ring Laser Gyro

4. Inertial Reference Measuring Systems

The following motion sensors and motion sensor systems may be potentially suitable for developing a portable motion compensation system for DREO's experimental ESM system:

4.1 Rate Gyroscope

One of the two basic building blocks of an inertial reference system is the rate gyroscope. The rate gyro provides an output signal whose magnitude corresponds to rotational velocity. The spatial orientation of the gyro determines the axis of rotation being measured.

There are a number of different technologies used for rate gyros. Traditional gyros use the angular momentum of a spinning rotor to determine angular rate. Ring laser gyros and fiber optic gyros make use of the Sagnac effect to measure differential phase in two counter-propagating laser signals. Vibratory (resonator) gyros measure the effects of Coriolis forces on the propagation characteristics of acoustic waves. Accelerometer gyros use two linear accelerometers placed on opposite sides of the gyro's axis of rotation and configured so that their differential acceleration is proportional to the rotation rate.

Companies which manufacture gyros often combine them into three-axis gyro assemblies, so that angular velocity may be measured in three coordinates.

4.2 Linear Accelerometer

The second basic building block of an inertial reference system is the linear accelerometer. As its name suggests, the linear accelerometer provides an output signal whose magnitude corresponds to acceleration along a single specific straight line. The measurement direction is determined by the orientation of the device.

Acceleration is typically quantified by measuring the displacement of a hinged mass within the device. The movement of the mass may be sensed by having it interact with a resonant circuit, either capacitively or piezoelectrically.

Accelerometers can be made extremely small. Analog Devices makes a family of monolithic accelerometers housed in a small 10-pin integrated circuit package.

4.3 Inertial Measurement Unit

An inertial measurement unit (IMU) is a system which combines three linear accelerometers, a 3-axis rate gyro assembly, and some associated useful signal processing. As the IMU moves in space its gyros measure its angular velocity and axis of rotation, and its accelerometers measure its acceleration vector. The IMU uses this information to compute, for a fixed time step, delta angle in three coordinates and delta velocity in three coordinates. (Delta angle corresponds to a change in orientation of the unit and delta velocity corresponds to a change in its velocity vector.) These deltas are computed at a fixed output rate, usually on the order of tens of hertz to 100s of hertz. On-board circuitry is included to compensate for temperature effects, turn-on and bias drifts, and non-linearities in the sensor components.

4.4 Attitude and Heading Reference System

An attitude and heading reference system (AHRS) is a system which combines a 3-axis rate gyro assembly and associated signal processing to compute attitude and heading. (It may also include three accelerometers.) As the AHRS moves in space it computes delta angle in three coordinates, similar to an IMU. The AHRS then integrates the delta angle to compute its orientation or pointing direction relative to the navigation frame.

An AHRS would appear to meet in concept many of the requirements of DREO's proposed motion compensation system.

5. Non-Inertial Reference Measuring Systems

All inertial sensor systems exhibit some drift over time in their measurement of the navigation frame. The following devices may be useful in placing bounds on this observed random drift:

Magnetic Compass:	Uses components such as fluxgates to accurately measure the direction to magnetic north. Manufacturers: KVH, Watson Industries.
Gyro Compass:	Uses a gyro to sense earth's rotation. The line of the axis of rotation is then determined, indicating the direction to true north. Manufacturers: Andrew.
Inclinometer:	Uses a mechanism such as the surface of a liquid or a pendulum to measure tilt angle. The device usually has two degrees of freedom, so that it is capable of measuring roll and pitch (although response is relatively slow). Manufacturers: KVH, Watson Industries.
GPS Receiver:	Uses GPS satellite signals to locate position.

6. Comparison of Gyro Technology

The following table provides a comparison of the relative merits of established rate gyro technologies.

Type of Gyro	Pros	Cons
Spinning Wheel Gyro	Capable of very low noise. One gyro can measure two axes of rotation.	High precision mechanical design with many small moving parts makes reliability and ruggedness an issue. Expensive.
Fiber Optic Gyro	Capable of very low noise. Very rugged and reliable.	Expensive, although price seems to be dropping.
Ring Laser Gyro	Capable of very low noise. Rugged and reliable.	Expensive.
Vibratory Gyro	Less expensive than other technologies. Available as COTS systems from several sources.	Noise is not as good as other technologies.
Accelerometer Gyro	May be extremely small and light, since the sensor and associated electronics can be integrated on a single monolithic chip. Inexpensive.	New technology that is not really available off-the-shelf just yet. Noisy.

7. Device Specifications Used by Manufacturers

The following is a descriptive list of specification parameters used by manufacturers to characterize their rate gyros and rate gyro-based systems. Unfortunately, not all manufacturers use the same set of specifications to characterize their devices. Some attempt is therefore made to at least provide correlation for noise specifications.

The parameters in this list are considered to be the most important in relation to DREO's motion compensation objectives. The parameters are listed according to how critical they were deemed to be, from most important to least important. By far the most critical parameter will be random walk or noise. This characteristic more than any other will limit accuracy and resolution in the final bearing measurement.

Random Walk: A measure of noise power associated with the gyro system's output, measured as an Allan variance in units of deg/√hr, deg/√sec, or deg/hr/√Hz. In an Attitude and Heading Reference System, as the measured angle rate is integrated to obtain heading information (or roll or pitch angle), this noise is integrated as well and produces heading errors. As a result, the random walk specification is the key limiting factor for accuracy in inertial measurements. The random walk value also affects how often the IMU must be re-calibrated, and how long it takes to re-calibrate (if re-calibration is required).

Many gyro manufacturers don't specify noise via a random walk parameter. Some provide an RMS output noise specification for the entire gyro output bandwidth, usually in units of deg/s. Still others, such as SAGEM, uses a random drift specification, in units of deg/hr.

Output Noise: Noise out of the rate gyro across its entire spectrum, in units of deg/sec. Assuming this is an RMS value, then as an approximation it may be reasonable to convert this value to a random walk value by squaring, dividing by the gyro's output bandwidth, and taking the square root. (See random walk.)

Random Drift: A measure of random drift in the rate gyro output, in units of deg/hr. It is not immediately obvious how this specification relates to random walk. However, because the units are similar, as a first order approximation it may be reasonable to assume that random drift and random walk (in units of deg/√hr) differ by no more than a factor of two. (See random walk.)

Bias Drift: A constant drift seen in the gyro's rate output. Bias drift varies with temperature, with turn rate and from turn-on to turn-on. However, the bias drift for a single device may be accurately measured and cancelled out.

Bandwidth: A measure of how quickly the gyro can respond to changes in turn rate, usually specified as a 3 dB bandwidth in units of Hertz.

Angular Rate: The operating range of the gyro, in units of ± degrees/sec.

Accel. Sensitivity: Drift in rate output attributed to a linear acceleration of the gyro, in units of deg/hr/g. This drift seems to be relevant only for spinning wheel gyros.

Mag. Sensitivity: Drift in the gyro's rate output attributed to the presence of a magnetic field, in units of deg/hr/Gauss. This drift seems to be relevant only for spinning wheel gyros.

8. Inertial Motion Sensors

The items in the following tables identify sensor products which were deemed to be suitable for developing a motion compensation system. The sensor products are separated into three groups: Inertial Measurement Units, Attitude and Reference Heading Systems, and Rate Gyros and Gyro Assemblies.

Inertial Measurement Units						
Manufacturer	Model No.	Axes	Specifications	Power	Size and Weight	Cost
Ring Laser Gyro						
Honeywell Inc. Military Avionics Tel. 612-951-5226	HG1700	6	Angular Rate: ±1,000°/s Random Walk: 0.125°/√hr Drift Bias: 1.0°/hr O/P Data Rate: 100Hz/600Hz O/P Format: RS-422, RS-485	±15Vdc +5Vdc <8W	3.7in dia. x 2.9in. ht. <33 cu.in <2.0 lb	
Fiber Optic Gyro						
Litton Guidance and Control Systems	LN-200	6	Angular Rate: ±1,000°/s Random Walk: 0.1°/√hr Drift Bias: 1.0°/hr Bandwidth: >500Hz O/P Data Rate: 100Hz/600Hz O/P Format: RS-485	±15Vdc +5Vdc 10W	3.5in dia. x 3.35in. ht. 1.54 lb	$30,000 (Mike Vinnins ballpark)
Resonator Gyro						
Watson Industries Tel. 800-222-4976 www.primenet.com/ ~watgyro	IMU-BA604	6	Angular Rate: ±100°/s Rate Resolution: <0.025°/s Az Accuracy: ±3% (compass) Output Noise: 0.03°/s Drift Bias: <0.5% FS Bandwidth: 70Hz O/P Data Rate: 56.89Hz O/P Format: RS-232	+12Vdc <600mA	6.5in x 6.5in x 3in <4 lb	$11,500 (ballpark by telephone) This device includes a magnetic compass and pendulous references.
Boeing North American Tel. 714-762-0761 (Harry Hughes)	DQI	6	Angular Rate: ±1,000°/s Random Walk: 0.03°/√hr Repeatability: 10°/hr Stability: 1 - 3°/hr Bandwidth: 50Hz O/P Data Rate: 100Hz O/P Format: AMRAAM	28Vdc 19W	3.2in x 3.5in x 3.8in 2.2 lb	$17,000 (ballpark by telephone)

Attitude and Heading Reference Systems						
Manufacturer	Model No.	Axes	Specifications	Power	Size and Weight	Cost
Fiber Optic Gyro						
Litton Guidance and Control Systems	LN-200	6	See entry in Inertial Measurement Unit table for specifications. This device is available with a software option so that the unit will perform as an AHRS.			$30,000 (Mike Vinnins ballpark)
Resonator Gyro						
Watson Industries Tel. 800-222-4976 www.primenet.com/ ~watgyro	IMU-BA604	6	See entry in Inertial Measurement Unit table for specifications. This device includes a magnetic compass and pendulous references, and includes software to enable the unit to perform as an AHRS.			$11,500 (ballpark by telephone)
Watson Industries Tel. 800-222-4976 www.primenet.com/ ~watgyro	AHRS-BA303	3	Angular Rate: ±100°/s Rate Accuracy: ±0.2°/s Az Accuracy: ±2% (compass) Att. Accuracy: ±0.3° (pendulum) Output Noise: 0.03°/s Bandwidth: 50Hz O/P Data Rate: 71Hz O/P Format: RS-232	+12Vdc 500mA	3.24in x 5.25in x 4.68in 1 lb	$8,800 (ballpark by telephone) This device includes a magnetic compass and pendulous references.
KVH Industries Inc. Tel.	Azimuth Digital Gyro Compass	3	Angular Rate: ±45°/s Accuracy: ±1° (compass) Resolution: ±0.01° Att. Range: ±45° Bandwidth: 20Hz O/P Data Rate: 10Hz O/P Format: RS-422	+12Vdc 300mA	1.74 kg	$3,000 (obtained from website)

Gyros and Gyro Assemblies						
Manufacturer	Model No.	Axes	Specifications	Power	Size and Weight	Cost
Fiber Optic Gyro						
Andrew Corp. Tel. 708-873-2307	Autogyro Navigator	1	Angular Rate: ±100°/s Random Walk: 0.33°/√hr Drift Bias: 0.005°/s Bandwidth: 100Hz O/P Data Rate: 10Hz O/P Format: RS-232	9 - 18Vdc	4.5in x 3.5in x 1.6in. 0.55 lb	$900 (ballpark by telephone)
Andrew Corp. Tel. 708-873-2307	RD 2000	1	Angular Rate: ±100°/s Random Walk: 0.08°/√hr Drift Bias: 0.002°/s Bandwidth: 100Hz O/P Data Rate: 10Hz O/P Format: RS-232	9 - 18Vdc 3W	4.4in x 4.3in x 1.7in 0.75 lb	$2,500 (ballpark by telephone)
Resonator Gyro						
BEI Systron Donner Inertial Division Tel. 510-671-6648 (David Antkowiak) www.beisensors.com	MotionPak	3	Angular Rate: ±500°/s Random Walk: 0.005°/s/√Hz Drift Bias: 1.8°/s Bandwidth: >60Hz O/P Format: analog	±15Vdc +5Vdc 3W	3in x 3in x 3.6in. 1.54 lb	$7,500 (ballpark by telephone)
Murata Tel. 770-436-1300	Gyrostar ENV-05S	1	Drift Stability: 10°-50°/hr			$300 (hearsay)
British Aerospace Systems and Equipment	VSG 2000	1	Angular Rate: ±100°/s Output Noise: 0.75°/s Drift Bias: 0.3°/s Bandwidth: >70Hz O/P Format: analog	9-18Vdc <100mA	1.8in dia. X 1.4in ht. 0.3 lb	£694 (info from Mike Vinnins)

Gyros and Gyro Assemblies						
Manufacturer	Model No.	Axes	Specifications	Power	Size and Weight	Cost
SAGEM Navigation and Defence Division	30 MS 57	3	Angular Rate: ±1,000°/s Bias Stability: 20°/hr Drift Bias: 0.3°/s Bandwidth: >100Hz O/P Format: RS-422	±15Vdc <10W	5.9in x 4.7in x 3.9in 1.7 kg	
Spinning Wheel Gyro						
SAGEM Navigation and Defence Division	30 BM 61	3	Angular Rate: ±120°/s Random Drift: 0.5°/hr Output Noise: <0.02°/s Drift Bias: 10°/hr Bandwidth: 100Hz O/P Format: RS-232, RS-422	±15Vdc <28W	4.8in x 4.6in x 3.7in <1.7 kg	
British Aerospace Systems and Equipment	FG 314	3	Angular Rate: ±100°/s Output Noise: <0.03°/s Drift Bias: 50°/hr Bandwidth: 125Hz O/P Format: Analog	18.2Vac 6.9Vac 7Vac	0.9in dia. x 1.0in ht. 1.7 oz	£4,400 (info from Mike Vinnins)

9. Using Platform Navigation System Data

On a ship platform, INS information is readily available and it is very accurate. It is available as a continuous analog signal, and in some cases it may also be provided as an RS-422 signal. On some of the larger ships, azimuth heading, roll and pitch are all available from the INS at several pick-off points around the ship. On smaller ships roll and pitch may not be measured.

On an aircraft, INS information is available from the 1553 data bus, but access is somewhat restricted and subject to more rigorous approvals because of safety issues. The DF system will probably have low priority access to the aircraft's bus, and it is uncertain what update rate may be allowed for motion compensation. Aurora's and fighters have full attitude information provided on their bus.

10. Conclusions

The Attitude and Heading Reference Systems seem to incorporate much of the functionality required by DREO's proposed motion compensation system. Of the identified AHR systems, those manufactured by Watson Industries and KVH Industries are probably most suitable because of their on-board compass. And between these two systems, KVH has a decided edge in price. Therefore, subject to meeting the requisite accuracy and resolution in heading, it appears that the KVH system is the most promising at this time for developing an ESM antenna motion compensation system.

This observation is based to some extent on the assumption that the mounting platform for the ESM system will be a ship. If the platform is to be an aircraft, the low bandwidth and relatively narrow angle ranges of the KVH system may become problematic in getting accurate inertial measurements. In this case the Watson Industries system, or perhaps even the Litton system may be a better choice. Both of these systems have been designed for aircraft applications.

Alternatively, there may be good reasons related to flexibility of packaging and design such that the best course of action is to build a custom AHRS out of individual rate gyros. A customized sensor package could be built to attach efficiently and with minimum added weight to the DF antenna.

If this decision were taken, then the Andrew fiber optic gyros would probably be a good choice. These gyros are rugged and reliable, with good noise characteristics, and three Autogyro Navigators would cost a relatively inexpensive $2,700 US.

The primary drawback to this approach is the additional development effort required to produce a working AHR system from individual rate gyro sensors. A power supply will need to be provided. Care will need to be taken to precisely mount the gyros at right angles to one another. The three outputs will need to be integrated to produce a delta angle signal. And signal processing software will have to be developed to calculate the inertial reference frame under dynamic conditions.

Regarding the use of platform navigation data for motion compensation, this option is probably only going to be workable if the platform is a ship, and only if the ship is large enough such that ship's data includes attitude information. Because the data format may vary from ship to ship, the interface between DREO's motion compensation system and ship's INS will likely be platform-specific.

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1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.) TACTICAL TECHNOLOGIES INC.	2. SECURITY CLASSIFICATION (overall security classification of the document, including special warning terms if applicable) UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

MOTION COMPENSATION STUDY - TASK ONE REPORT (U)

4. AUTHORS (Last name, first name, middle initial)

VIGDER, BILL

5. DATE OF PUBLICATION (month and year of publication of document) JANUARY 1997	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.) 12	6b. NO. OF REFS (total cited in document)

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

CONTRACTOR'S REPORT

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

DEFENCE RESEARCH ESTABLISHMENT OTTAWA
NATIONAL DEFENCE
SHIRLEYS BAY, OTTAWA, ONTARIO K1A 0Z4 CANADA

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant) 5BD11	9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written) W7714-6-0010
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.) DREO CONTRACTOR REPORT 97-621	10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

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GPS
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#504178