ASTROINERTIAL NAVIGATION FOR CRUISE APPLICATIONS

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ABSTRACT

Astroinertial navigation systems provide the greatest accuracy and a bounded position error over an extended use-time and distance. These systems are autonomous, passive, non-jammable and automatic.

The key element of the system, the astroinertial instrument, is a three gimbal stable inertial platform with an integral two degree of freedom day-night star tracker that operates automatically world wide.

The system provides navigation, guidance, and control with the best accuracy available in any self-contained navigation system, from subsonic through hypersonic speeds. The present operational system described in this paper, NAS-26, provides bounded cruise navigational performance--better than 1,000 ft. CEP--throughout flights of short or long duration (specific performance classified).

A next generation system with improved performance is also described.

INTRODUCTION

For thousands of years man has relied on the stars as a primary source for determining his position on the surface of the earth. The United States' first intercontinental missile, the SM-62 Snark, used the first automatic astroinertial navigation system with three telescopes to overcome the inadequacies of the gyros and accelerometers of the 1950's to bound position errors to 1.4 nautical miles. The system to accomplish this weighed almost a ton with reliability that was in hours or tens of hours.

Today, thirty years later, Northrop has a fourth generation astroinertial operational system, the NAS-26, with performance, weight, and reliability that are each improved by a factor of over ten to one from the original Snark system. What is more surprising is that today's NAS-26 System is lower in production price than the Snark System of the 1950's. The NAS-26 system is shown in Figure 1.

PERFORMANCE

The NAS-26 astroinertial systems underwent an extensive flight test program in 1977. At the conclusion of the flight testing, the system was declared fully operational and in complete compliance with the performance specifications. Table 1 below shows the unclassified performance capabilities that may be released. Obviously, the actual performance is classified.

The system weights 184 pounds, volume is 3.9 cubic feet, and has a proven reliability of over 300 hours MTBF.

The NAS-26 system provides both navigation and guidance, and can also control and point other onboard avionics and sensors with the best accuracy available in any operational self-contained navigation system, from subsonic through hypersonic speeds. The system described provides bounded cruise navigational performance--better than 1,000 ft. CEP--throughout flights of short or long duration (specific performance classified).
Secret classified performance capabilities are better.

The inertial platform provides instantaneous navigation data, i.e., velocity, heading, and position. The astrotacker provides precise position updates, accurate heading, and calibration of gyro drift rates for near perfect gyro performance. The composite hybrid system results in bounded position performance that is essentially independent of flight time with only second order noise growth.

The NAS-26 system has a stellar ephemeris of 61 stars permanently stored in the computer. This provides a minimum of two star availability, world wide, day or night. Normally six to ten stars are available at any one time. The system will automatically sequence through in order each star within the field of view and then continuously repeat the cycle. The astrotacker tracks star magnitudes from -1.46 to +3.5 and in sky backgrounds of 8,000 to 430 ft-Lamberts, respectively. The system automatically excludes stars that are within 12.5° of the sun, within 3° of other stars of similar magnitude, or near planets or the moon. Also, once per second a test is made to verify that the star is within the window field of view under conceivably changing vehicle attitudes.

The sequence of operations in star tracking is:
- Read sidereal (solar) time from the computer clock
- Determine present position from the computer
- The computer identifies catalog stars in field of view
- The computer selects brightest trackable star within the field of view
- Set photosensor gain for selected star magnitude and measured sky background
- Open shutter and measure sky-background light level in star vicinity
- Set scan rate for star magnitude and measured sky background
- Commence search.

The NAS-26 astrotacker search pattern is shown in Figure 3. The aspect ratio and size of the search pattern depends on the data provided from the Kalman filter. In simple terms the aspect ratio depends on the system uncertainties at the time.

When a star signal is detected in the search, the astrotacker changes to the confirmation mode. The primary purpose of this mode is to verify that the signal is in fact the star and not noise. The confirmation mode accomplishes this by generating a horizontal pattern requiring four detections in five passes and that the magnitude of the signal is correct for the particular star.

Once the confirmation mode has verified that it is the star, the astrotacker switches to the track mode (star position determination). Ten horizontal and ten vertical passes are made at the start...
The NAS-26 Astroinertial System may be described as a hybrid inertial navigation system that utilizes frequent star measurement updates in the stellar navigation mode. Inertial only navigation is used as a back-up degraded mode and/or in conditions where stars are not visible due to total cloud cover.

The NAS-26 provides continuous navigation, velocity, and attitude reference information. It is designed to interface with other avionics, such as Air Data Computer, Magnetic Compass, Flight Director Unit, Horizontal Situation Indicator and other display elements.

It also provides automatic vehicle guidance through control of the autopilot, automatic sensor control, sensor stabilization, image motion compensation, and a data reference base.

When interfaced with the Compass and Airspeed Units, it provides the following modes of navigation:
- Astro-Inertial-Airspeed
- Astro-Inertial
- Inertial Only
- Dead Reckon
- Attitude Heading Reference.

Initially, present position is supplied by the operator via navigation control display unit; thereafter alignment, both ground and airborne, and navigation, can be fully automatic. Highest priority is given to the most accurate navigation mode attainable. Alternatively, the operator may select the mode desired.

The inertial-computer system is configured in a wander azimuth, local gravitational mechanization, a choice reflecting the dependence on stellar-inertial as the primary mode. The star ephemerides for 61 stars are permanently stored in computer memory, thereby providing automatic 24-hour celestial navigation reference without geographic limits. Star ephemeris tables are updated (refilled) annually. The star tracker, in addition to "bounding" position errors during its operation, also provides precision gyro drift rate calibration which contributes to significantly improved inertial-mode performance if this mode is required, as, for example, during periods of cloud cover. This star-calibration of the inertial gyro persists long after interruption of star tracking.

NAS-26 includes a Kalman filter software mechanism. This filter process, used for ground and air alignment, for stellar-inertial, and for inertial navigation modes, is an 18-state variable Kalman mechanization that operates in real time in...
the computer and determines the relative weightings to be placed on the measurements. When airspeed is used as a velocity data source, for example, optimal estimates are fed back to correct both systems. Similar operations on the stellar measurements, barometric altitude, etc., provide extremely accurate navigational performance in the primary modes and provide optimized transition to degraded modes in the event of loss of any of the subsystem elements or by virtue of unavailability of cloud-free line of sight to the stars. At 25,000 ft. the worldwide mean probability of a clear line of sight is 68 percent at any instant of time, and improves rapidly to 100% as altitude increases. As implied above, the system maintains accuracy with intermittent tracking.

There is a large variety of output signals available from NAS-26. These outputs are computer controlled and are, therefore, software flexible. The use of the signals includes steering signals to enable great circle, heading, and point steering in addition to the conventional situation and navigational data. Most of the outputs are available for stabilization, mode control, motion compensation, data annotation, etc., of sensor systems. Therefore, the NAS-26 System can operate as a complete automated guidance system, not just as a navigation system.

The NAS-26 also serves as a source for an accurate reference data base for inflight vehicle parameters. The data available includes vehicle attitude, velocities (vertical, cross-track, ground speed), heading, acceleration (three axis), distance to destination, distance/bearing to points of interest, cross-track range, sensor mode, etc.

Figure 4 shows a simplified NAS-26 system block diagram.

SYSTEM CONFIGURATION

The NAS-26 consists of four major assemblies (LRU's): the Astrometric Instrument (AI), Digital Computer, Power Supply Unit (PSU), and Control Display Unit (CDU) (Figure 5).

The NAS-26 electronic design features are:

- Serial Communications for minimum inter-LRU wiring

Figure 5 NAS-26 System

- Hybrid Microelectronics for reduced size and weight, and increased reliability
- Comprehensive BITE to assure fault detection and to enhance flight safety
- Partitioning into functional entities to facilitate isolation and to simplify LRU shop testing
- Use of worst-case practices to insure reliability and long life.

ASTROINERTIAL INSTRUMENT (AI)

The NAS-26 Astrometric Instrument (AI) is an inertial measuring unit consisting of an enclosed three-gimbal stable reference platform and star tracker.

The AI is constructed in three main sections: a middle support housing consisting of the gimbaled stable reference platform and star tracker; an upper cover fitted with an optically polished viewing window for the star tracker; and a lower housing containing related electronic circuitry and a recirculating heat temperature control system operating across a Peltier thermal-electric heat exchanger, cooled from externally supplied air.

The middle housing contains the gimbaled stable platform and the astrotracker. The order of gimbaling inward from the middle housing support is: inertial roll, pitch and yaw, star tracker azimuth, and star tracker elevation. Roll, yaw and azimuth gimbaling have complete rotation freedom; pitch motion is mechanically limited to +850; elevation motion is limited to -20 to +1000. Rotational torque is applied to the gimbals and tracker axes in accordance with computer commands by pancake-type direct drive DC torque motors. The gimbals and tracker axes are also equipped with pancake-type multipole resolvers for angle pickoffs and gimbal angle transformations. Transmission of electrical signals and power between the instrument housing, the gimbals, and the astrotracker is achieved by means of slip rings. These slip rings are mounted integrally within each gimbal axis.
The inertial platform is a bowl shaped casting having a central hub section extending downward from the bowl and several web frames radiating from the hub for mounting gyros and accelerometers. Fixed in the inertial platform assembly are two two-degree-of-freedom precision position gyros and three single-axis pendulous proof-mass accelerometers arrayed with their sensitive axes paralleling the reference axis of the platform. The major components of the astrotracker are installed within the tracker bowl, whereas the amplifier, filter and preamplifier comprise the shape, and smaller in size than the inertial platform similar to the viewing slot in an astronomical observatory). To avoid saturation of the photosensor by excessive light entering the telescope, a solenoid-operated shutter closes over the window of the photo-multiplier case when not actually scanning or whenever the sky brightness exceeds a predetermined level, such as scanning in close proximity to the sun.

The astrotacker assembly can best be visualized as a second platform similar in material and shape, and smaller in size than the inertial platform. The astrotacker is mounted trunnion-fashion within the tracker bowl so that the telescope can be rotated in elevation about a horizontal axis. The optical barrel is mounted on one side of the trunnion and the photo sensor and shutter are mounted on the opposite side. An alignment mirror, whose normal is parallel to the optical axis and perpendicular to the elevation axis of the telescope, is located near the outer end of the telescope.

The optical barrel of the star pointing telescope is 2 inches in diameter and about 2.5 inches in length. It is a modified Cassegrian telescope consisting of a primary aluminized mirror, a doublet lens backed by a secondary mirror, a folding mirror and field stop re-imaging lens system.

The primary mirror in the telescope base reflects the field of view into the secondary mirror. The secondary mirror is centered in the objective aperture and reflects the field onto a diagonally positioned flat mirror. The diagonal mirror, having an opening only for the telescope barrel. In addition, the tracker bowl incorporates a domed sun-shade with an open slot for telescope visibility (similar to the viewing slot in an astronomical observatory). To avoid saturation of the photosensor by excessive light entering the telescope, a solenoid-operated shutter closes over the window of the photo-multiplier case when not actually scanning or whenever the sky brightness exceeds a predetermined level, such as scanning in close proximity to the sun.

The photomultiplier contains a photo-cathode located such that the optically directed rays from the telescope fall upon it. The signal collected from the anode is used as the input to an electronics package mounted near the base of the photomultiplier beneath the sunshade. A buffer amplifier, filter and preamplifier comprise the phototube electronics package. The output of this preamplifier is used in the detection circuitry of the tracker electronics located in the lower housing.

The upper housing is a cover fitted with an optically polished viewing window. A 95-degree cone of vision is attainable through this nine-inch diameter astro-window.

The lower housing contains those electronic circuits related to the AI function which are not thermally sensitive. These include the tracker detection and servo electronics, platform electronics, interface electronics, and the digital-to-analog and analog-to-digital conversion electronics that, along with a 2,000 word microprocessor, provide the communications and interface circuits with the Digital Computer. The lower housing contains a blower and heat exchanger structure to provide cooling by drawing ambient air through the housing.

The NAS-26 uses two Kearfott Gyroflex Mod 2 two-degree-of-freedom dry tuned gyro and three Kearfott Model 2401 accelerometers. See Table 2 and Figure 6.

<table>
<thead>
<tr>
<th>Gyro Parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>Random Drift (°/hr)</td>
<td>0.09</td>
</tr>
<tr>
<td>Fixed Restraint (°/hr)</td>
<td>0.02</td>
</tr>
<tr>
<td>Mass Unbalance (°/hr/g)</td>
<td>0.02</td>
</tr>
<tr>
<td>Anisotropic Drift (°/hr/g^2)</td>
<td>0.015</td>
</tr>
<tr>
<td>Temperature Sensitivity</td>
<td>0.08</td>
</tr>
<tr>
<td>Volume (Cubic inches)</td>
<td>5.5</td>
</tr>
<tr>
<td>Size</td>
<td>2.14 in dia. x 8 in length</td>
</tr>
<tr>
<td>Weight (oz)</td>
<td>8</td>
</tr>
<tr>
<td>Setting Time (min)</td>
<td>1</td>
</tr>
<tr>
<td>Operating Life (hrs)</td>
<td>15,000</td>
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</tbody>
</table>

In the event of a Digital Computer failure, the NAS-26 System is mechanized such that the system gracefully degrades to an Attitude Heading Reference System (AHRS) with the inertial platform stabilized by the AI electronics. The AI electronics is also mechanized such that in case of
single and double precision logical and arithmetic capabilities, roll table mechanization, and high-speed multiple shift operations. In addition, a high throughput rate is achieved through direct memory access and provision is made for a full complement of efficient program interrupts, indexing and subroutine access features. A summary of the NDC-1070 characteristics is given in Table 3.

<table>
<thead>
<tr>
<th>Table 3 NDC-1070 Computer Characteristics</th>
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</thead>
<tbody>
<tr>
<td><strong>Clock Frequency</strong></td>
</tr>
<tr>
<td><strong>Memory Type</strong></td>
</tr>
<tr>
<td><strong>Size</strong></td>
</tr>
<tr>
<td><strong>Word Length</strong></td>
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<tr>
<td><strong>Cycle Time</strong></td>
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<tr>
<td><strong>Access Time</strong></td>
</tr>
<tr>
<td><strong>Arithmetic Mode</strong></td>
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<tr>
<td><strong>Number System</strong></td>
</tr>
<tr>
<td><strong>Data Formats</strong></td>
</tr>
<tr>
<td><strong>Add</strong></td>
</tr>
<tr>
<td><strong>Multiply</strong></td>
</tr>
<tr>
<td><strong>Total Instructions</strong></td>
</tr>
<tr>
<td><strong>Instruction Formats</strong></td>
</tr>
<tr>
<td><strong>Addressing</strong></td>
</tr>
</tbody>
</table>

A chronometer is not required as airborne equipment with NAS-26. The chronometer is used as aerospace ground equipment and is brought to the vehicle to initialize NAS-26 system time in the NDC-1070 computer. The computer maintains time through power droppouts for 15 minutes with an internal battery.

**CONTROL DISPLAY UNIT (CDU)**

The NAS-26 Control Display Unit gives the operator the ability to interface with the navigation system, control the navigation operating mode, change the sensor control parameters, and change the flight route. The operator may also effectively display many parameters of interest.

A combination of fifteen keyboard buttons, one rotary switch and one incremental switch allows the insertion or display of parameters as listed below. The panel includes three alphanumeric displays, mode displays, and status displays.
The status displays include star tracking status, temperature status, and system malfunction status.

The alphanumeric displays are able to display, as a minimum, the following data:

- Present Position - Latitude, Longitude
- Time and Day
- Heading
- Altitude
- Sensor Control Point (CP) Data - Ident. No., Latitude, Longitude, Altitude, Range
- Verification Fix Point (FP) Data - Ident. No., Latitude, Longitude, Altitude, Range
- Destination Point (DP) Data - Ident. No., Latitude, Longitude, Altitude, Range.

The following data is capable of being inserted through the panel:

- Latitude
- Longitude
- Heading
- Time
- COOLING AND POWER

The cooling requirements for NAS-26 are as follows:

**Astroinertial Instrument (Hermetically Sealed Section)**

- Inlet Air Temperature: 30°F to 90°F
- Inlet Air Flow Rate: 2 to 5 pounds/minute

**Power**

The electrical power required for the NAS-26 is as follows:

<table>
<thead>
<tr>
<th></th>
<th>Average (Watts)</th>
<th>Peak (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AI &amp; PSU</td>
<td>500</td>
<td>800</td>
</tr>
<tr>
<td>Digital Computer</td>
<td>235</td>
<td>270</td>
</tr>
<tr>
<td>CDU</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>Total</td>
<td>785</td>
<td>1140</td>
</tr>
</tbody>
</table>

**Calibration**

The NAS-26 Astroinertial Instrument (AI) is calibrated at the factory using specialized factory checkout equipment. Calibration is accomplished with the AI middle housing (containing the inertial platform and tracker assemblies) sealed under internal thermal control, and using the AI electronics for platform and tracker control. Thus, the AI is calibrated in its operational environment without simulation of hardware or thermal control. Calibration is accomplished under control of a microprocessor and calibration software that connects to and controls the AI, the tilt table, and autocollimator light source. The parameters that are calibrated include the internal light reference, telescope resolver angular errors, gimbal resolver angular offsets, and the accelerometer and gyro parameters. The accelerometer and gyro parameters include null bias, scale factor, misalignment, nonlinear corrections, drifts, etc.

Field verification tests are made periodically on the AI and if the parameter is found to exceed specification, and not correctable in the field, the AI is returned to the depot for recalibration.