

# Novel Variations on Old Architectures/Mechanizations for New Miniature Autonomous Systems

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## Elaborated Abstract

We at **TeK Associates** have investigated cutting edge navigation concepts since the 1970's [1]-[2], including early use of GPS [47], [48] as well as its use at high update rates to compensate for the higher drift-rates associated with use of a less expensive INS. (e.g., under sub-contract, used Kalman filter-related covariance analysis to perform quantitative analysis of the relative pointing accuracy provided by each of several alternative candidate INS platforms of varying quality (and cost) by using high quality GPS [P(Y)-code, differential, or kinematic] fixes at a high rate to enhance the INS with frequent updates to compensate for degradations incurred with time due to specific inherent gyro drift rates characterizing each INS). We are cognizant of operational principles of GPS [26]; of Inertial Navigation Systems (INS) [6], [33] and their underlying linearized error models [6]; of Kalman filter/estimation theory [22], [24], [29]-[31]; of reduced-order filters [23], of host platform [27] and environmental constraints and countermeasures [21], [28] for theoretical analysis, simulation, and software implementation:

- Trail-blazed development of a particular Kalman filter accouterment: **Two Confidence Region (CR2) Failure Detection**, from first principles by developing a test statistic and subsequently specifying False Alarm and Correct Detection Probabilities that are traded-off in specifying **CFAR** time-varying decision threshold for comparing it to in making fail/no-fail decisions [10]-[19].
- Surveyed and analyzed alternative **Decentralized Filtering approaches** to identify those satisfying constraints possessed by NAV applications of interest to NADC (for JTIDS RelNav) [8] and to Wright-Patterson AFB for **MUFBARS** and **ICNIA** for Advanced Tactical Fighter [25], first under **ITT** contract then for **TRW**.
- First to recognize the utility of combining earlier “failure detection methodology” with that of “decentralized estimation”, thus reaping a satisfying firm theoretical foundation for “**redundancy management**” for **airborne navigation applications** consisting of an INS with position fix/resets from several alternative external nav aids for updates [9].
- Trail-blazed analysis and evaluation of multi-sensor data collection using INS/GPS to support a particular **airborne platform and its mission of collecting terrain data** [6].
- Published a **critique of existing GPS** [20], [21].

We are familiar with problems associated with many emerging AUV's that need remedying:

1. **Lack of redundant gyros (and accelerometers)** in using only three orthogonal single-degree-of-freedom conventional mechanical spinning rotor gyros so UAV design is not robust with respect to incurring even a single routine gyro failure (or accelerometer failure) which can then jeopardize the success of its mission;
2. **Lack of any coherent calibration procedure** to get the inertial navigation system up and operating well (i.e., accurately) after having been stored on a shelf for awhile.

Use of Rockwell Micron INS, which consists of electromagnetically supported spherical gyros, possess two input axes per gyro and, as such, is known as being a two-degree-of-freedom gyro and, as a consequence, having just two gyros provides a redundant input axis. So use of, say, three Micron gyros can then provide full redundancy (when 2 input axes from different gyros point in each of the 3 directions) [41]-[46]. **Ring Laser Gyros (RLG)** possess excellent shelf-life characteristics that tend to exhibit the same constant random white noise level and (random) constant bias trends, as originally established computationally during initial calibration of the system, as performed, perhaps, years earlier. Unfortunately, the accuracy of a RLG goes directly with the area circumscribed by its laser light path so a small RLG has low accuracy and vice versa.

The typical mechanical spinning-rotor gyroscope found within classical conventional Inertial Navigation Systems (INS) is constructed by suspending a relatively massive spinning rotor inside three orthogonally mounted support rings called “gimbals”. Mounting each of these rotors on axes with high quality bearing

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surfaces with low friction insures that very little resisting torque is exerted on the inside rotor as the rotor continues to spin. Electrical “torquers” are utilized to initially spin up the innermost rotor to its nominal speed and to maintain its angular velocity, as continuously monitored by electrical or mechanical “pick-offs”. Modern day INS gyros take many different forms [33] based on whatever particular inherent physical principle is being exploited, such as that for wine glass acoustic frequency vibrating gyros, for electro-statically supported spherical gyros, for electro-magnetically supported spherical gyros, for ring laser gyros (typically providing a modicum of dither to avoid laser lock between the two opposing paths), for fiber optic gyros, for atomic quantum spin gyros, etc.

Another important aspect is just how two (or more) gyros (and their associated accelerometers) are ultimately implemented or bound together within an Inertial Navigation System (INS) complex such as in a Space Stable configuration, in a Local-Level configuration (as either Wander Azimuth, Free Inertial, North Slaved, or North Pointing), or in a Strap-Down configuration; and in its corresponding associated Navigation filter (i.e., Kalman filter) formulations, which can be implemented in three different alternative ways but with the differential feedback form being prevalent nowadays. New insights have been recently revealed in Ref. [3] into how modern MEMS gyros may now be implemented in Strapdown configurations without the same hassles or operational constraints being imposed that were historically associated with handling the classical spinning rotor gyros discussed above.

A 1960's era Draper Laboratory study and report had concluded that a preferred optimal configuration for redundant gyros (with only one-degree-of-freedom input axes) was being located and oriented in a certain prescribed way as an orthogonal triad placed along each of the 12 faces of a regular dodecahedron. Perhaps as Draper Laboratory now wrestles with the cheap and plentiful MEMS gyros (that have a coarse accuracy), Draper should consider again invoking their own historical 40-year-old solution (but they have not done so yet).

Reference [3] contains a good modern perspective. What is conveyed in Ref. [3] is possibly of revolutionary importance! However, the assertions and conclusions in this paper should be viewed as being very controversial and examined closely. Also see Refs. [4], [5], [34], [36]-[39], [41] for other perspectives. Strapdown is indeed the dominant INS mechanization for all airborne applications these days as has been the case for the last 25 years. However, Strapdown, by bolting the gyros and accelerometers directly to the body frame of a particular platform and accounting for platform motion relative to these INS sensors, is a little different and more computationally intensive than the other available INS mechanizations (all being nonlinear). The challenges and issues associated with Strapdown have been addressed in the open literature of navigation as the solutions evolved. Yet the many alternative mechanizations for an INS, already listed above, and ways to use Gimbals that used to be the weak link (since four nested gimbals were needed to avoid incurring gimbal lock), and, in the past, there was significant friction to be encountered and overcome in their use, and mechanical torquers were needed too. Technology for all of the above has greatly improved by now and may be worth another look.

If we temporarily dispense with or suspend the requirement that an airborne INS may only be implemented in Strapdown, then the following techniques can be utilized:

- **Gyro Monitoring** for a Local Level mechanization of three single-degree-of-freedom gyros, each mounted orthogonally to the others, involves using a fourth independent but similarly constructed gyro, mounted in the same plane as two of the input axes of the other gyros participating in the computed navigation solution and then periodically rotating the so-called extra monitor gyro to align itself with first one and then the other of the two "horizontal gyros" of the INS complex with their input axes in the same plane to obtain the sum and difference of the respective constant bias gyro drift-rates. The gyro biases of the two gyros whose input axes are in the horizontal plane can then be computationally estimated by solving the two appropriate linear equations in two unknowns [32], [42]. A psi-angle analysis yields the appropriate linear equations to be used for this, where the psi angles are the standard gyro-frame to computer-frame misalignments (described by linear INS model ODE, driven by the drift rate noises and biases, and scale factor errors).
- The **HAD/HAP** procedure (of the late William Zimmerman) could be invoked again to measure and compensate for the effects of biases.

- Principles incorporated into the **Carousel INS** (patented by William Zimmerman, Robert Shipp, et al in the 1960's) can be invoked. The entire complex is rotated at a constant rate effectively averaging out the effect of constant bias drift-rates present in the single-degree-of-freedom gyros within the plane of rotation.

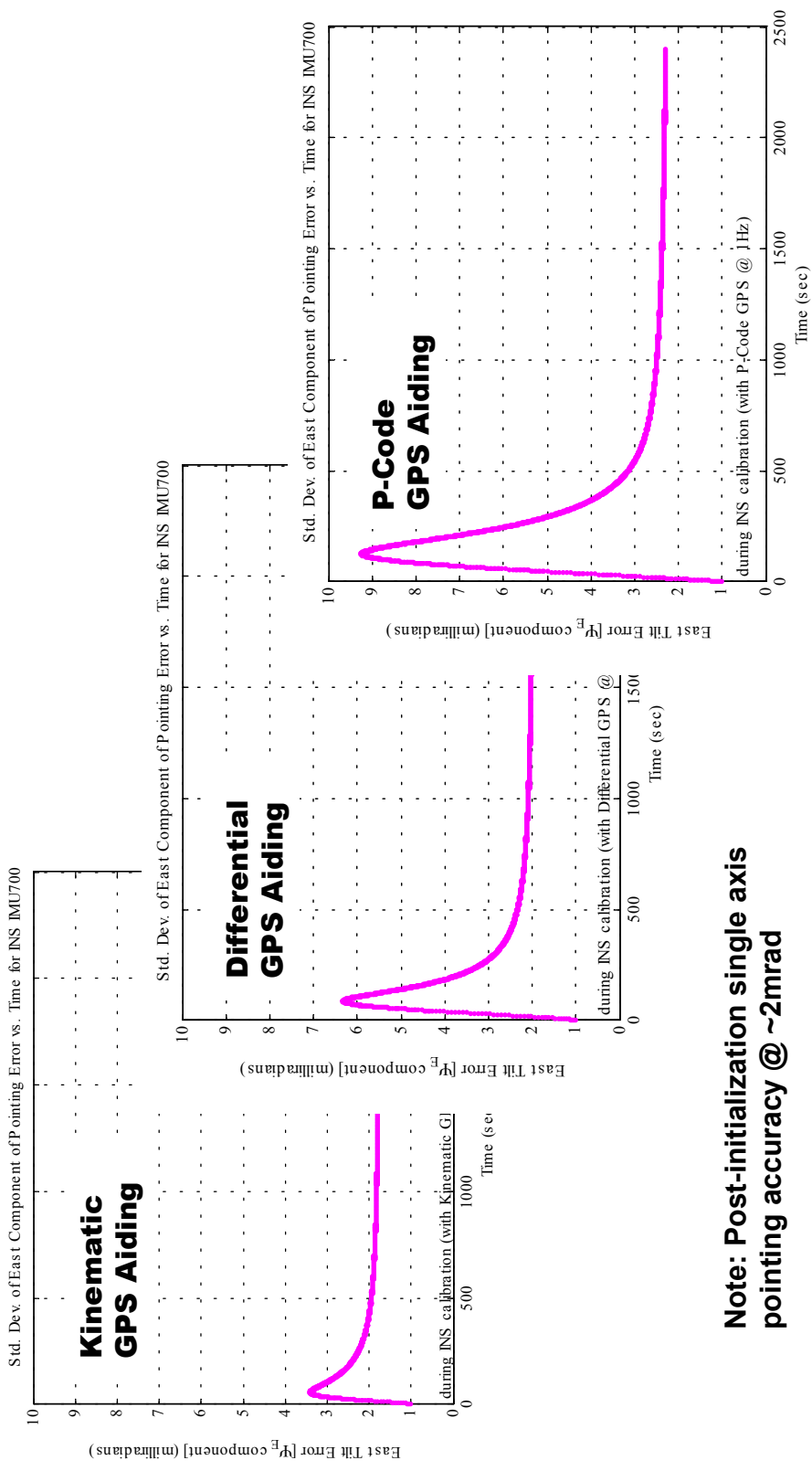
The first two of the above three techniques were developed for submarine navigation, where the submarine “flies” through the water like an aircraft flies through the air, as its fluid. A single monitor gyro would need to be located on each of the 12 faces of the dodecahedron upon which a triad of gyros and accelerometers are mounted. Each monitor gyro would need to be rotated to align correctly with the other gyro’s input axes along the particular dodecahedron face of concern. Similar steps could be taken to implement a Carousel-like INS complex or **HAD/HAP** mechanizations for each triply orthogonal pair of input axes occurring on each face of the dodecahedron. Moreover, for logistics and re-supply, it is not out of the question to have appropriately hinged faces of the dodecahedron made of stiff plastic or some sort of polymer so that it packs flat and, perhaps, benefits from this unfolding during initial calibration of all the participating **MEMS** gyros. However, a solid dodecahedron would suppress vibration and flexure. Or unfolded could later wrap around a solid core. Ultimately, the final NAV solution of primary reliance could be the average of the 12 participating independently computed separate NAV solutions offered on each face of the dodecahedron (each with covariance sigma squared); and, as a consequence, the final average would have an accuracy improvement consisting of sigma squared divided by 12 (std. dev. = sigma divided by square root of 12). This same technique can also be used to improve the accuracy of RLG’s through averaging to yield one consensus output for primary reliance. There is still a need to damp the “vertical channels” [35], [40].

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# Single Axis Pointing Accuracy for IMU700



**Note: Post-initialization single axis pointing accuracy @ ~2mrad**

# IMU/GPS Covariance Analysis

