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THAT ALL-IMPORTANT INTERFACE

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ABSTRACT

The goal of nav systems integration should include growth flexibility, to accommodate the future addition of data sources and operations not envisioned in original configurations or plans. That aim is seriously compromised when information available from extant sources is deficient in content, form, timeliness, or precision. Unfortunately this is a common occurrence, not an occasional oversight; information is typically conveyed in ways that became standard long before modernization. Prime examples are attitude (expressed in terms of the familiar roll-pitch-heading convention) and velocity components in single precision.

These and other instances of accepted procedures are reviewed, along with an illustration of how various practices impose fundamental but completely unnecessary limitations on achievable integration performance. In accordance with available means of correcting all deficiencies, which have been widely known for years, straightforward measures are proposed whereby standards can be updated. The related issue of mounting location for critical elements on nonrigid structures is also briefly addressed. In all cases under consideration, the intent is to eliminate impediments to true system integration.

INTRODUCTION

Complete sets of interface variables have been defined for inertial reference systems[1], LORAN[2], GPS[3], and myriad other navigation subsystems. In the selection of those variables, one item that has obviously exerted considerable influence is the form of expressions familiar to users. While there certainly is merit in presenting data in ways to which users are accustomed, algorithm designers often prefer the information in different forms. The chosen inertial data interface, for example, is clearly adequate for many purposes, but compares poorly against achievable state estimation performance needed to calibrate in preparation for outages. These and several other issues are explored herein, with suggestions offered to resolve seemingly conflicting interface requirements. In addressing these issues, no criticism is expressed, implied, or intended to be directed toward any document cited or not cited herein, or any group responsible for document generation. Rather, since the influence of today's standards will not be limited to today's equipment, a critique of present standards as applied to future systems is the intent.

Extant interface standards [1-3] are adequate if all the following conditions are satisfied:

- operations are restricted to navigation *per se*
- there is no need to capitalize on update information capable of providing state estimates with better accuracy than that permitted by standard I/O precision
- either there will be no need to add sensors to a future configuration, or an *ad hoc* integration will suffice for any future added information

Extant interface standards are inadequate if any of the following conditions are present:

- In addition to navigation *per se*, nav information is used for related operations such as motion compensation, stabilization of image or other sensor data, antenna servo control, etc.
- there is a desire to estimate Kalman filter nav states to accuracies better than the standard I/O precision presently allows
- Kalman filter design parameters may change (e.g., to accommodate new input data specifications, measurement schedules, etc.)
- there may be a future need to add sensors (as yet unspecified) to the configuration, and to integrate the added information optimally or near optimally (whether in estimation or to enable multisensor fault detection, isolation and reconfiguration schemes, or to provide analytical redundancy)
- the nav sensor could be used in an operating mode differing from that originally envisioned (e.g., differential GPS).

NAV DATA FLOW and USAGE

In addressing the impact of alternate data forms and expressions for nav, one approach might be to compile a list of

- every source of data involved in the overall nav function (including units, useful accuracy, and resolution),
- all operations wherein each of those sources is put to use (e.g., Table III-1 on page 336 of Ref. 4),

and

- all timing information relevant to each source (e.g., which clock and what protocol controls its data flow, applicable data rates, latency, accuracy of its time tag).

Although a properly detailed design would specify these requirements and assess their influence on system performance, the main thrust of this communication needs only a subset of the full nav interface. Of primary importance here will be alternate means of defining terrestrial position, velocity, direction (verticality and azimuth), and navaid fix information. Usage of the data need not be limited to nav *per se*, but can include stabilization or aiding of the sensors used to obtain those fixes (e.g., receiver tuning adjustments necessitated by doppler shifts from own-vehicle motion; GPS code track; radar range gate control or antenna servo compensation for own-vehicle rotation, etc.).

It clearly is of utmost importance that the functions just exemplified, and in fact all functions to be performed, be allowed to proceed under all circumstances with all the promptness and accuracy afforded by the data sources supplying the stabilizing information. Ironically that straightforward goal is routinely thwarted by standard interface specifications. A few examples:

- It has long been known that both longitude and the North-referenced azimuth direction become ill-defined as position approaches either pole. Yet longitude is used to express position while vehicle orientation is expressed as true heading and vehicle velocity vector direction is expressed as a ground track angle (again with respect to geodetic North).[1]
- It is likewise well known that no Euler angle triad can provide all-attitude characterization. The roll-pitch-heading standard, for high-performance aircraft in particular, is vulnerable to singularity at extreme pitch attitudes. Although this is not critical for airliners, ships, or land vehicles, it would seem preferable to accept a readily available standard that can accommodate *every* application.
- Velocity vector information *internal to the INS* appears in Cartesian form. The same form is highly desirable for Kalman filter states.[4] Although users may wish to observe *output display* data in cylindrical coordinates (groundspeed, track angle, vertical speed) and nonuniform units (e.g., Knots for groundspeed, ft/min for vertical speed), there is no valid reason why a systems integration designer should be denied access to the Cartesian vector data - and with the full available precision, rather than the truncated information (0.125 Kt LSB) on the present standard interface.

- To date, no standard LORAN interface exists that provides access to time-of-arrival (TOA; pseudorange) or time difference (TD) measurements. The current commercial standard[2] is based primarily on ARINC Characteristic 561, "Air Transport Inertial Navigation System" and provides position in latitude/longitude only. The lack of raw pseudoranges or TDs severely limits capabilities of hybrid systems, such as GPS/LORAN.[5]
- The standard GPS interface does contain raw pseudoranges, but they are incomplete for differential GPS. Because reference time for ephemeris data (updated once per hour) is not included, the nav set could be incorporating differential corrections derived from time-staggered ephemerides; this could introduce errors of order 2 - 5 meters, unacceptable for precision approach. Also, the doppler count (integrated delta pseudorange) should be continuously accumulated to facilitate differential carrier phase tracking.

Consider now a situation in which a designer, inheriting only the single precision velocity data in cylindrical coordinates available from the standard INS interface, attempts to improve upon some algorithm as originally delivered (e.g., by modifying parameters in GPS velocity update). The pseudorange rate fixes are accurate to within 2 or 3 cm/sec, but the velocity is propagated in time with a resolution of 6.43 cm/sec (= 0.125 Knot, also expressible in this example as a frequency error on the order of $^1/_3$ Hz). The designer cannot quite fully exploit the doppler updating information, but that is not the major issue. Those familiar with the nav update operation will recognize limitations that are more serious:

- Any attempt to propagate the velocity dynamics in terms of groundspeed and ground track angle will produce nonlinearities in Kalman filter state extrapolation, due to the cumbersome relations between those velocity variables and position, or between those velocity variables and INS verticality error states.
- but Any attempt to reëxpress groundspeed and ground track angle in terms of IMU velocity dynamics before propagation will impose significant added computational burden (involving square roots and trig functions, at the IMU data rates), which at best would merely regenerate information already present within the INS.
- and Either way, the single precision form of the data produces irrecoverable losses in achievable performance.

To illustrate this last point, note that a 16-bit roll angle with a range of values equal to $\pm\pi$ radian produces an attitude LSB of $2^{-15}\pi$ rad $\approx$ 100 μrad. That resolution is adequate for many uses of attitude data, but not for nav update if the Kalman filter must prepare for outages of a few minutes. During intervals t of that order one LSB of leveling error produces position errors of order $0.0001\ (^1/_2 gt^2)$, or about 30 meters in four minutes. That is not at all trivial for many GPS applications, i.e., it is enough to affect code track aiding. Also recall that, with extensive computations, errors can reach some multiple N times the LSB; in that case the allowable 4-minute outage interval is reduced by the same factor N. For such reasons, LSB values are commonly chosen an order of magnitude *below* troublesome levels. For future systems the guideline can be: except for huge data volumes or extreme data rates, bits are cheap and becoming cheaper; use enough so that word length is not a performance issue.

One approach often proposed for integrated navigation would combine inertial data from the standard interface with direct location pseudomeasurements from a receiver. This method often leads to cascading or otherwise combining outputs of Kalman filters that were separately designed, with potentially severely degraded results. For instance a Kalman filter designed for horizontal, enroute GPS navigation is most likely not properly tuned for the higher gain approach operation, where the emphasis is on vertical performance. Too much phase lag would be introduced into the guidance output which would have an unpredictable destabilizing effect on the approach operation.

As another example of extended operation, a designer might be given an additional task of sensor stabilization, to be accomplished using the available nav data. Here the adequacy issue subdivides into considerations of computational merit and accuracy. For the former it is unconditionally true that Euler angles offer the poorest choice in comparison with other attitude expressions (Table *2*, next section). For accuracy, adequacy of Euler angles depends on the application. First it must be realized that own-vehicle rotations can be counteracted with either sensor-mounted gyros or repetitively computed attitude correction data, for servo-driven sensors *only*. Ref. [6] describes both approaches to antenna stabilization; a similar description would be applicable to directive GPS antennas, discussed in Ref [7] to enhance SNR under adverse conditions. When repetitive computation of rotational compensation is the selected approach, or when the sensor elements are hard mounted to the vehicle frame,[1] then any relative rotational motion between sensor and *its local* attitude data source (e.g., due to structural deformation) must be less than the allowable stabilization error. If structural deformation between sensor and the INS can exceed allowable stabilization error, then the INS cannot qualify as the *local* attitude data source. Compensation then calls for a sensor-colocated IMU, transfer-aligned to the master INS[8] — and here both the 100 μrad and the 0.125 Kt LSB are decidedly too crude. Finally, even in the subset of cases wherein stabilization via standard INS attitude would be feasible (i.e., servo-driven rather than hard-mounted sensor elements, with sensor-to-INS deformation below allowable error, and operation precluded in any region near Euler angle singularity), the function scope would typically be restricted to stabilization of antennas, not imaging sensors. The 100 μrad granularity will generally produce unacceptable jitter in a stabilized image.

The combined influence of all considerations cited above appears compelling, especially if prospective future needs are addressed. If that theme should need a tag line for reinforcement, the following question is suggested for consideration: who would wish to buy an integrated GPS/INS unit if the Kalman filter residing therein used the data in the form now being sent to the standard interface output?

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[1] In analogy with replacement of gimballed platforms by strapdown IMUs, electronically steerable arrays are often used in preference to mechanically slewed antennas.

CANDIDATE REVISIONS

Described in this section are alternate means of expressing 3-dimensional position, velocity, and attitude, plus raw receiver data; pseudorange (PR), accumulated delta pseudorange (ADPR), time-of-arrival (TOA), or time difference (TD). Designated receiver signal array dimensions are based on reception of all available signals (all-in-view). Although GPS and LORAN measurements are made with respect to time, the measurement units are converted to meters, through multiplication by the speed of light. "Enhanced" precision here precludes 16-bit words; some evaluation would be advisable to pinpoint a standard.

TABLE 1: I/O SIGNALS UNDER INVESTIGATION

SIGNAL	SOURCE	DIMENSION	PRECISION	UNITS
Position	INS	3 to 9	Enhanced	See Table 2
Velocity	INS	3	Enhanced	meter/sec
Attitude	INS	3 to 9	Enhanced	See Table 2
TOA or TD	LORAN	ALL-IN-VIEW	Enhanced	meters
PR	GPS	ALL-IN-VIEW	Enhanced	meters
ADPR	GPS	ALL-IN-VIEW	Enhanced	meters

For LORAN, most receivers measure the time of arrival of the pulses with respect to the receiver clock. TOAs contain more information than their pairwise differences (TDs), since differencing removes the clock phase. For example, two LORAN station TOAs in combination with a stable receiver clock provide 2D position (e.g., the French LORAN chain). If the two TOAs are combined into one TD, positioning would not be possible. Also, one LORAN station TOA could be used in combination with three GPS pseudoranges to obtain 3D position and time.

Obviously no attempt is made here to provide a complete I/O spec; only the key signals cited above are under review. Also, no attempt is made to discourage adding customary outputs (e.g., direct position from receivers), as long as the signals defined here are provided. Again, there is no reason to discontinue or even modify the customary means of display (e.g., the aforementioned velocity data in cylindrical coordinates), and nonuniform units can be computed from the proposed new standard signals for display. The user won't have to reorient thinking *but designers will* (no doubt gladly, in most cases).

To accommodate differential GPS, the measurement data should not be corrected for ionospheric and tropospheric delays, which are included in the differential correction. Also, the interface should provide full ephemeris data for each satellite being tracked, with measurement status (Carrier-to-Noise ratio, etc.). This *complete* raw measurement data available from the GPS sensor would facilitate all possible uses of the data.

In defining candidate forms for the data under review, the easiest decision was made first: elimination of the singularity at the poles. Difficulty with both longitude and the North azimuth reference can be circumvented by adopting either a Cartesian position vector (e.g., ECEF) or the widely used wander azimuth convention. For the latter, permissible choices for azimuth rate of the nav coordinate frame include:

- zero (Ref. [4], pages 84-87),
- Earth sidereal rate only (so that lab tests can conform to the geographic frame),
- continuous carouseling (so that level gyro drift biases will average toward zero),
- a rate chosen in conformance to a selected UTM grid reference.[9]

While most designers would accept Cartesian velocity components in wander-azimuth axes and metric units, both position and attitude data can be offered in a wider variety of forms. Rather than selecting one form for either, relative merits of various alternatives are tabulated in preparation for evaluation in some future standards forum. Except for the Cartesian position vector, previously mentioned, means of expressing attitude and Earth position are similar; they include *(1)* Euler angles (roll/pitch/heading for attitude; latitude/longitude/wander angle for position; *(2)* sines and cosines of those angles; *(3)* nine corresponding direction cosines; *(4)* four corresponding quaternion elements[4]; and *(5)* three of those quaternion elements with LSB overridden.

To explain the last item, it is often desirable to express attitude with the fewest possible variables, i.e, three (for minimum interface traffic and/or for ease in time-interpolation of values) — but no 3-parameter attitude form is free from singularity or discontinuity[10]. It is both correct and numerically sound, however, to omit the largest of the four quaternion elements and compute its value from the normalization condition (the sum of squares of the four elements must add to unity). All that would remain, then, is the sign of its square root. That sign (one bit), and the index of the missing largest element (two bits), could be encoded into the LSB's of the three quaternion elements appearing on the new standard interface.

TABLE 2: MEANS of EXPRESSING POSITION and ATTITUDE

FORM	STABILITY	EFFICIENCY	CONCISENESS	FAMILIARITY
Euler Angles	Marginal	Poorest	Excellent	Excellent
Sines & Cosines	Marginal	Marginal	Poor	Excellent
Direction Cosine Matrix	Excellent	Excellent	Poorest	Excellent
4 Quaternion Elements	Excellent	Very good	Good	Poor
3 Quaternion Elements	Excellent	Very good	Excellent	Poorest
Cartesian Vector (POSITION ONLY)	Excellent	Very good	Excellent	Good

The Euler angles and their trig functions are included for comparison only; due to their singularity, they are not recommended for the new standard. The other conventions are described, with requisite mathematical formulations, in Ref. [4]; *pp* 44-46 for quaternion attitude, *p* 86 for wander-azimuth, *pp* 84-87 for relations between alternate wander-azimuth forms (Euler angle, quaternion, direction cosine). For the Cartesian position vector, *pp* 222-225 relate to dynamics with the geodetic reference, while *p* 246 expresses the relation of the geocentric vector to the geodetic latitude and longitude.

In proposing interface changes, it is probably worthwhile to anticipate — and disarm — the argument that straightforward transformations could be used to recover the data in other forms desired. There are various problems with any such plan:

- Computations may seem reversible, but only abstractly. In practice there are computational delays, myriad approximations adopted for efficiency or expediency (often with incomplete documentation), and numerical degradations from irrecoverable word truncation (Examples include expression of velocity in single precision, and omission of key information necessary to recover the original data, such as missing ephemeris reference time, ionospheric correction data, etc.).
- Attempts to extract original data by inverting perceived computational operations would often be performed by individuals not completely familiar with the original development, and might thus appear as "black art" (at least from the standpoint of data timing in the presence of multiple asynchronous CPU clocks). The process could be error prone, and the added computation would undermine the purpose of standardizing the interface in the first place.
- Even if all computational steps could be meticulously retraced, the added effort required would be costly — and all that would be accomplished would be recovery of the original data, already present on the other side of the interface.

CONCLUSIONS

Characteristics of interface standards are reviewed and recommendations are made for revisions. Measures suggested here do not preclude direct output of location from receivers, but output should not be *only* that. Furthermore, there are no constraints on federated structures [Ref. 12]; both raw measurement data and computed position from each separate device can be made available to users. The cost of modifying interface pales in comparison with accumulated cost imposed by loss of flexibility for modifications in all applications.

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