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AN EXPERIMENTAL STUDY OF AN INTEGRATED GPS/INS SYSTEM FOR SHALLOW-WATER AUV NAVIGATION (SANS)

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ABSTRACT

The Naval Postgraduate School's "Phoenix" AUV has thus far been operated only in a test pool environment. In preparation for open water testing, currently planned for mid-1996, a series of towfish experiments are being conducted in Monterey Bay to investigate the feasibility of integrated GPS/INS transit mode navigation, in significant sea states, using a GPS antenna mounted only a few inches above the AUV body. In this configuration, either wave action or deliberate submergence will cause loss of GPS position fix information for periods extending from several seconds to a few minutes. The main research question being investigated is, therefore, to determine whether or not a low cost strapped down IMU can be used to navigate accurately between GPS fixes. Our goal is to achieve inertial navigation accuracy comparable to GPS accuracy during periods between successive GPS fixes. Experimental results reported in this paper indicate that this is feasible.

CONTENTS

INTRODUCTION

The NPS "Phoenix" AUV is an experimental vehicle designed primarily for research in support of shallow water mine countermeasures and coastal environmental monitoring [1],[2]. In [3], we describe an approach to determining the position of submerged detected objects by executing a "pop-up" maneuver to obtain a GPS fix, and then extrapolating this fix back to the submerged object location using recorded inertial data. As explained in [3],navigation accuracy during such a surfacing maneuver is strongly enhanced by the use of accurate depth information available from low cost pressure cells. However, this form of "aided" inertial navigation [4], is not applicable to a surfaced AUV. Of course, inertial navigation is not needed at all in circumstances where reliable reception of GPS satellite signals is possible, but this does not apply to AUVs unless they are fitted with a mast to extend a GPS antenna well above the effects of wave action. This is not an attractive option for military operations, and in any event may be mechanically difficult.

Recognizing the problem of intermittent GPS satellite tracking for surfaced (or cruising near the surface) AUV navigation, we have designed an experimental system which uses a low cost strapped down inertial measurement unit (IMU) to enable inertial navigation between GPS fixes. This IMU also is appropriate to pop-up navigation, so finding a means of navigating near the surface provides a complete solution to the overall navigation problem associated with transiting an AUV to a shallow water work site, recording the position of detected submerged objects, and then returning to a recovery site where stored mission data can be uploaded. The remainder of this paper describes the hardware and software associated with the proposed Shallow-water AUV Navigation System (SANS), and presents bench test data for key subsystems as well as limited results on at-sea experiments relating to the effects of wave action on GPS satellite tracking. Further at-sea testing of a complete SANS system is expected to take place in Monterey Bay during summer 1995. Results obtained, as well as software and hardware details, will be reported in [5],[6]

SANS SYSTEM DESCRIPTION

Hardware

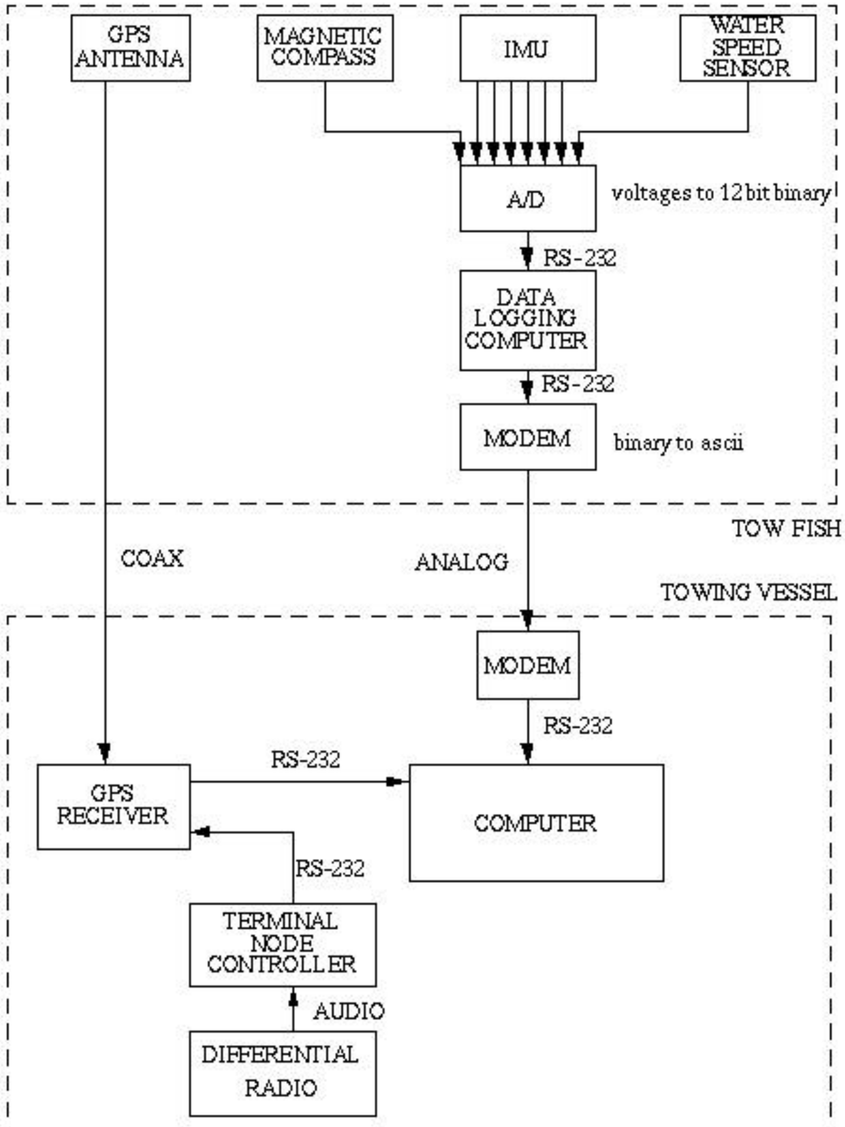

Figure 1: Towfish Experiment Hardware Configuration

Figure 1 shows a block diagram of the hardware being assembled for at-sea testing of the SANS system concept. Figure 2 presents a photograph of the major components of the corresponding physical system. Comparison of Figure 1 to the system described in[3] reveals a number of differences. First of all, to enable experiments using a towfish rather than an AUV, the SANS system has been broken into two subsystems in which a minimum number of components have been placed in the towfish itself, and the remainder are in the towing vessel. This results in a smaller towfish, with reduced power requirements, and also allows for human monitoring and interaction during the course of an experiment. Of course, when SANS is integrated into Phoenix (or any other AUV), the modems and towfish data logging computer shown on Figure 1 will no longer be needed, and the computer in the towing vessel will be replaced by the AUV onboard navigation computer.

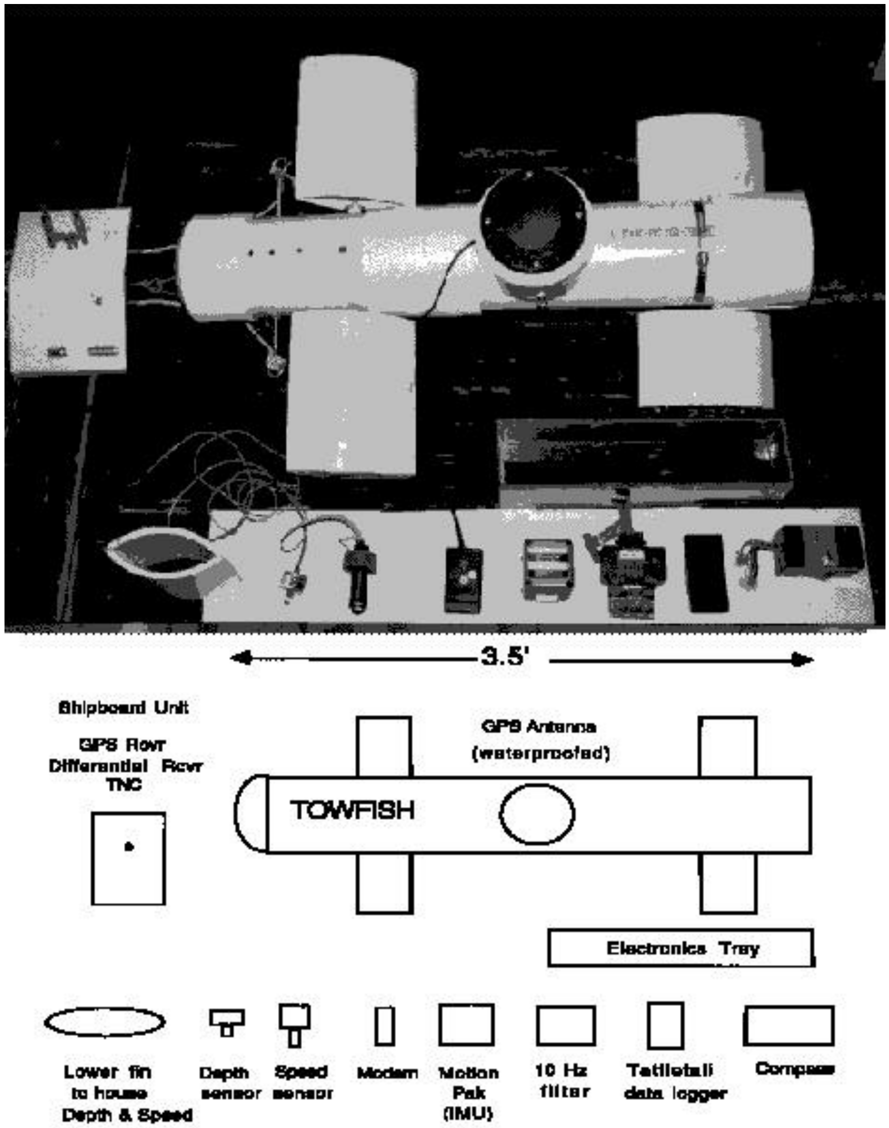

Figure 2: Towfish and SANS Components

Other differences from [3] include replacement of the depth cell used for pop-up navigation by a water speed sensor. This is because depth rate cannot be used for water speed estimation during surfaced navigation. Naturally, a complete SANS would include both sensors to enable both navigation modes. Additionally, estimation of water speed from depth rate by deliberate "porpoising" during submerged navigation may be useful. We intend to investigate this possibility after SANS is installed in Phoenix. Another change to the earlier SANS concept is the replacement of rotating gyros by miniaturized vibratory angular rate sensors for improved reliability and to eliminate AUV maneuver limits imposed by rotating gyros [3]. These sensors are packaged together with three precision linear accelerometers in the integrated IMU shown in Figure 2[7].

Relatively calm conditions in Monterey Bay have allowed us to conduct towfish tests to date from a small sailboat. During these tests, and for the tests planned for summer 1995, an Intel 386 based laptop PC has proven adequate for data collection. Processing of test data has so far been accomplished off-line with a Sun 4 workstation. When SANS is installed in Phoenix, an onboard notebook workstation (Sun Voyager or similar system) will replace both of these computers for real-time navigation. This computer will also perform other mission control functions as described in [2],[8], while vehicle control will continue to be accomplished by the current Phoenix OS-9 system hosted on a Gespac 68030 computer [1],[2].

Navigation Software

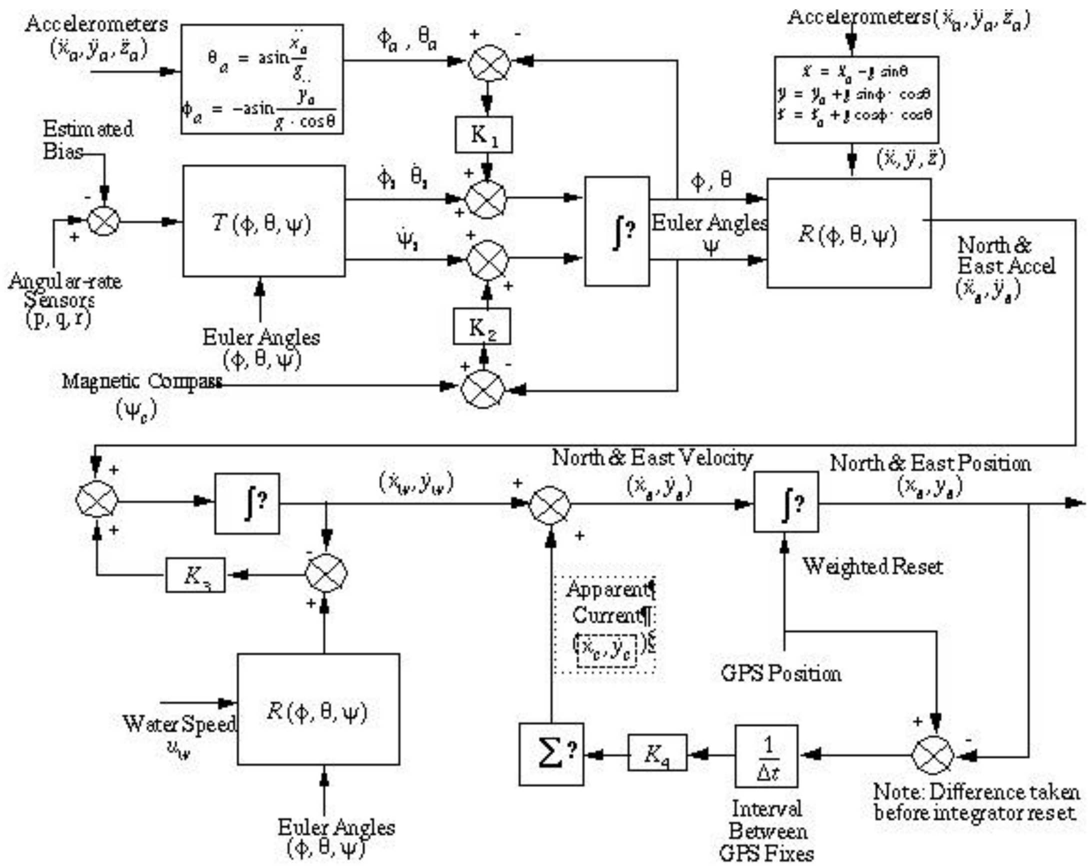

Figure 3: Nine-State Velocity-Aided Navigation Filter

Figure 3 is a dataflow diagram for the SANS navigation software. As can be seen, the seven continuous-time state components of this filter consist of three Euler angles, two horizontal velocities, and two horizontal positions. The two discrete-time state components are composed of estimated current in the east and north directions. Of course, in the actual SANS digital filter implementation, the continuous-time integration shown in this figure is approximated by numerical integration, so in this sense the seven "continuous" time state components are also "discrete" time states. However, it is important to realize that minimum integration sampling times are limited only by computer and A to D hardware characteristics, while diving and wave action result in GPS signals being received only sporadically. Thus the two "discrete" time states are updated aperiodically as is characteristic of "discrete event" dynamic systems [9]. This being the case, it is difficult to apply Kalman filter theory [4] to obtain optimal time-varying values for the gain matrices Ki shown in this figure. Instead, constant gains will be computed initially from bandwidth and steady-state error considerations as described below, and later "tuned" by off-line processing of data from sea trials. If this is found to be inadequate, further studies to characterize system noise sources will be needed to permit the derivation of optimal gains.

Examination of the continuous state part of Figure 3 shows that the Euler angle and linear velocity outputs are fed back to the corresponding integrator inputs. Thus if the gain matrices K1, K2, and K3 are all diagonal, each of these integrators is in fact a low pass filter for each of its inputs. This is done to prevent unlimited growth of state estimates in the presence of unmodeled bias errors in state derivative inputs to integrators. On the other hand, each integrator also is furnished with an independent source of low frequency information to correct for long term decay of state estimates resulting from this feedback. This approach is usually referred to as "complementary" filtering [4], or sometimes as "crossover" filtering [10].

Generally speaking, if k is a component of a diagonal gain matrix K, then the time constant of the corresponding closed loop state estimation filter is the reciprocal of k. That is [4],

$$\tau = \frac{1}{k} \quad (1)$$

For time intervals somewhat less than *tau*, each integrator output is approximately the integral of its state derivative input. However, for intervals longer than *tau*, this component of state estimates experiences substantial exponential decay, and is replaced by the "complementary" input providing reliable low frequency information concerning the value of the associated state variable. Thus the filter is said to "crossover" at an angular frequency, *omega c*, where

$$\omega_c = \frac{1}{\tau} = k \quad (2)$$

A more quantitative way to view the meaning of the crossover frequency is to use frequency domain analysis [4]. Again referring to Figure 3, if *phi s* is the component of *phi* (roll Euler angle estimate) due to integration of the roll rate sensor output, *phi dot s*, then [10]

$$\frac{\phi(s)}{\phi_s(s)} = \frac{\tau s}{1 + \tau s} \quad (3)$$

while for the roll signal from the accelerometer triad, *phi a* ,

$$\frac{\phi(s)}{\phi_a(s)} = \frac{1}{1 + \tau s} \quad (4)$$

Comparing the right hand side of Eq. 3 with Eq. 4, it can be seen that the former is a high-pass filter with a "corner" frequency of *omega c*, while the latter is a low-pass filter with the same corner frequency. Thus the filter gain for *phi a* is higher than that for *phi s* at frequencies below k, while the reverse is true for frequencies higher than k. It is important that the right hand sides of Eq. 3 and 4 sum to unity for all values of s, since this implies no "frequency distortion" in the estimation of the roll Euler angle. Of course the same analysis applies to all of the six other continuous-time state components. Since Figure 3 represents a nonlinear filter, and GPS fixes are available only at unpredictable times, as noted above, there is no easy way to directly apply optimal filter theory to select the best value for k. Rather, in a given operational situation, this will be accomplished, at least initially, by qualitative analysis and experimentation.

With respect to the discrete state part of the navigation filter of Figure 3, GPS receivers have internal Kalman filters to smooth position data and estimate velocities, usually designed with no knowledge of vehicle dynamics or operational environment. On the other hand, with regard to ocean current estimation, if K4 is diagonal, then a gain of unity reflects complete confidence that GPS signals provide a precise measure of this effect, while a lesser gain results in exponential convergence to an estimated current (low pass filtering). Likewise, in resetting the north and east position from GPS, in general, for independent errors, the relative weight given to the most recent GPS position in comparison to the integrator output should be inversely in proportion to the error variances of each of these two signals [4].

As a final remark on filter design, it should be noted that the integration of linear velocity in Figure 3 is reinitialized on each GPS fix. Thus there is no need for feedback around this filter to counter long term drift effects.

SUBSYSTEM CHARACTERISTICS

IMU Static Testing

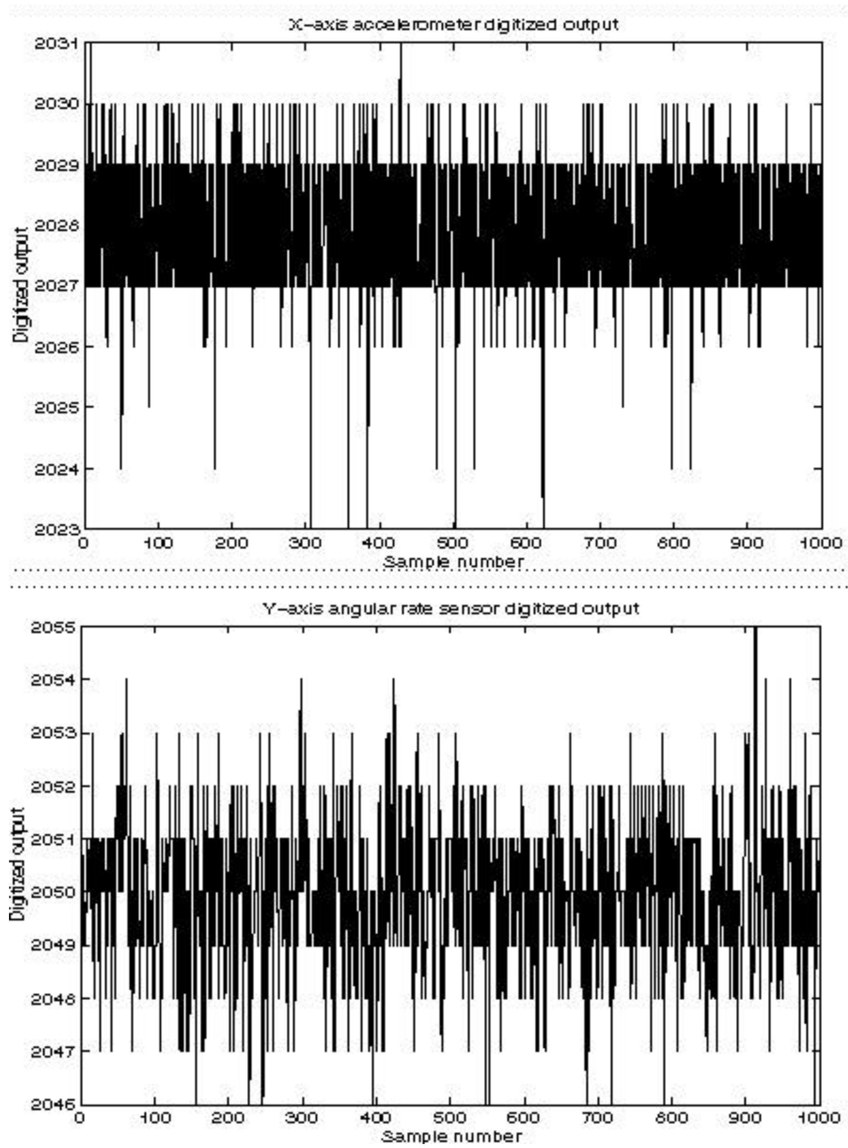

Figure 4: Typical IMU Bench Test Results Recorded Over 83 Seconds at 12Hz Data Rate

For cost and availability reasons, a single-sided 12 bit A to D converter [11] was selected for the breadboard SANS shown in Figures 1 and 2. Figure 4 shows a sample of typical results obtained from bench testing of an accelerometer and a rate sensor. In this test, data from all six channels of the IMU was collected using a Tattletale data logging computer [12]. As can be seen, the acceleration signal fluctuates an average of about one bit. This low level of accelerometer noise is due in part to the fact that each of the six output channels of the IMU is externally filtered by an active analog anti-aliasing filter with a bandwidth of 10 Hz. This circuit also converts the two-sided IMU analog output to a single-sided signal within the 0 to 5 volt range of the A to D converter [6].

The x-axis (longitudinal) accelerometer signal shown in Figure 4 was obtained with the accelerometer set on a table with the positive z axis pointing downward. Thus the output should nominally be zero, which corresponds to the integer value 2048 for this A to D converter. It can be seen that the output is actually centered around 2028, which represents an apparent error of around one percent. However, this is not a correct analysis of this effect. In fact, the output mean indicated could be due either to a tilt in the supporting surface or to an amplifier imbalance. Either of these effects would be eliminated in a prelaunch alignment and initialization phase before conducting a SANS mission. The real significance of Figure 4 is that limiting A to D precision to 12 bits seems to be justified, since it can be seen that typical IMU sensor noise reaches or exceeds the value of the least significant bit, at least with 10 Hz anti-aliasing filtering.

GPS Receiver Performance

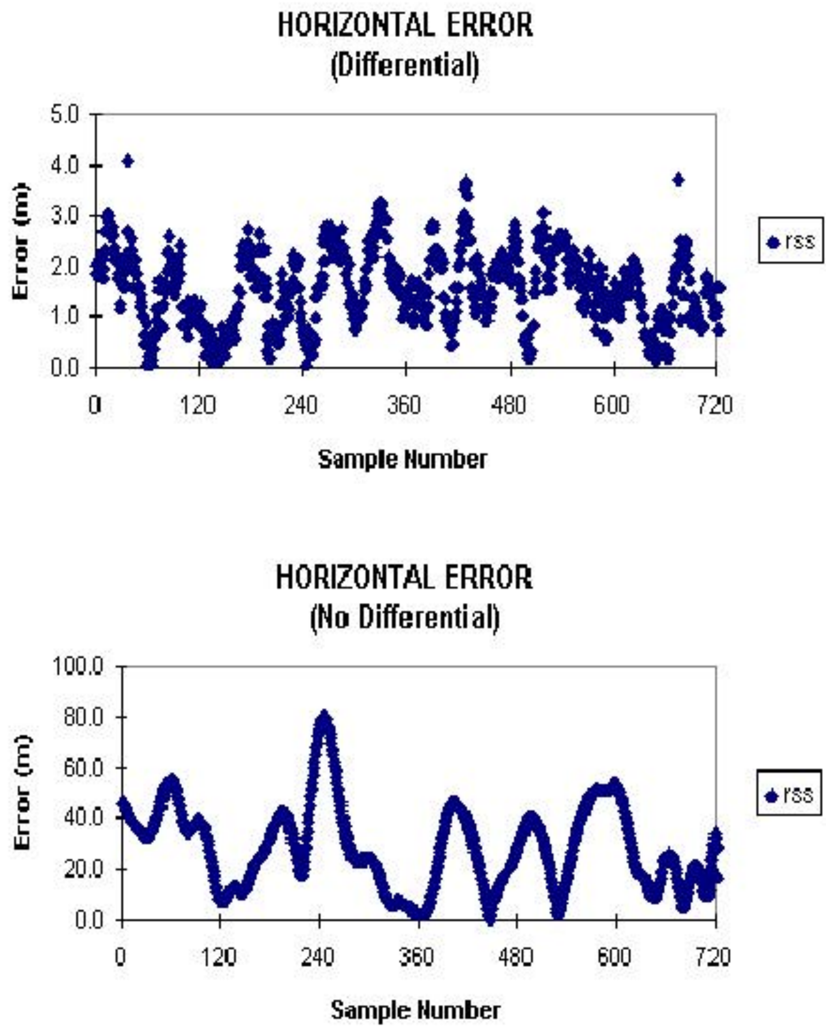

Figure 5: Typical GPS Bench Test Results Recorded over one hour at 5 second intervals

As described in [3], we have found that the Motorola PVT6 GPS receiver possesses generally desirable characteristics for the SANS system [13]. Specifically, as can be seen in Figure 2, it is physically quite small. It also possesses a low power sleep mode with the time to first fix after one hour of power off typically on the order of 30 seconds [3]. This long time is needed to acquire ephemeris (orbital) data from new satellites which may have come into view since the last GPS fix [14]. Accuracy in latitude and longitude has been observed in static testing to be around 30 meters rms using the standard positioning service (SPS) [3]. Figure 5 shows recent bench test results relating to raw GPS position estimates obtained with an antenna mounted on top of a five story building at the Naval Postgraduate School. Figure 5 also shows the improvement in horizontal position error (root sum square of orthogonal horizontal error components) which results from the use of differential mode using a Trimble RL base station about 3 km away. As can be seen, differential correction (DGPS) reduces rms radial position error to around 1.4 meters, corresponding to rms latitude and longitude errors of approximately 1 meter. These errors are generally consistent with the findings of an earlier, more comprehensive, study of a variety of DGPS systems [15].

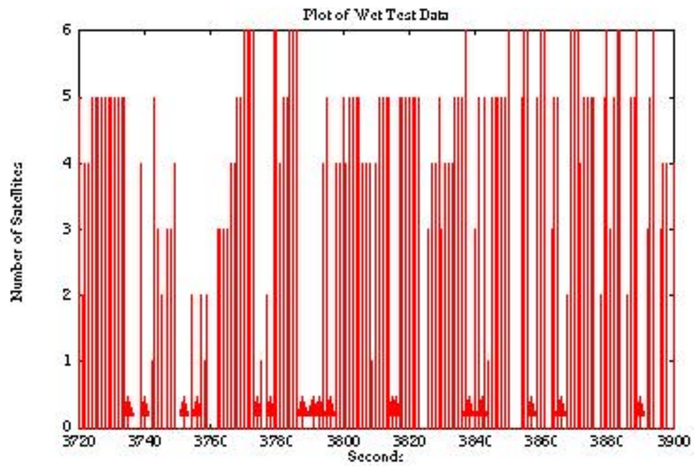

Figure 6: Typical Very Short, Shallow Dive Tracking Results
(Vertical arrows represent antenna surfacing.)

An important question relating to GPS navigation with the antenna essentially awash, as is the case for SANS, is whether or not satellite tracking can be maintained in the presence of wave action. To investigate this issue, we first conducted bench tests in which a plastic pan of seawater was placed over the GPS antenna. For satellites at small angles from the vertical, it was found that tracking could be maintained reliably for water depths of less than 5 mm. [16]. For satellites nearer the horizon, it was found that the slant distance through the water was the limiting factor in determining reception, and that this distance also can be up to 5 mm. without seriously affecting reception. Following these tests, the GPS antenna was mounted on an earlier simplified towfish [16], and subjected to short dives in which submergence typically lasted from 2 to 5 seconds. Figure 6 [16], shows the results of these tests. As can be seen, once satellite tracking is lost due to diving, the minimum of three satellites needed for surfaced navigation is typically regained in 2 to 5 seconds after surfacing. A fix is produced at that time if the satellite ephemeris data is available in the receiver memory for three or more of the satellites being tracked. These results encourage us to believe that wave action will not present a serious problem to GPS reception for SANS.

Other Components

The modems used are Pocket Peripherals Model PM14400FX [17], operating at a 9600 baud data rate. Communication from the towfish to the towing vessel is via a 100 ft. analog cable using X-Modem protocol. This has the consequence that 128 byte packets are transmitted at roughly a five Hz rate to the laptop computer in the towing vessel. Each of these packets contains eight samples of each of the eight inputs to the towfish A to D converter as shown on Figure 1. Thus an average sampling rate of 40 Hz is achieved for each of these signals. This represents a two times oversampling of the 10 Hz bandwidth analog signals, thereby ensuring that noise aliasing will not be significant in any subsequent digital processing [4] . As described in [3], the magnetic compass used is a KVC C100. The water speed sensor is a paddlewheel type used for small boat applications [18].These, and other system components shown in Figure 2, are based on proven technology and are expected to perform well in the SANS environment.

PERFORMANCE ANALYSIS

Attitude Estimation

As explained above, referring to Figure 3, it is our intention to find suitable values for the gain matrices Ki, and the weighting for reset of position estimates from GPS, by means of off-line processing of towfish data. This will involve trying different gain values and comparing the variance of the resulting position estimates with recorded DPGS position fixes being treated as true location. In order to keep the dimensionality of this process low, it is important that this gain selection process proceed sequentially. That is, from Figure 3, it is evident that the error characteristics of the towfish Euler angle estimates depend only on K1 and K2, and not on K3 or K4. Examination of Figure 4 shows that a filter time constant of the order of 10 to 100 seconds would reduce accelerometer noise to the level of quantization error, or lower. However, another consideration in choosing this time constant is the need to discriminate adequately against the effects of horizontal plane accelerations in inducing errors in the apparent vertical direction as sensed by accelerometers. For example, if a longitudinal or lateral acceleration of .02 g is sustained for longer than the filter time constant , then approximately a 1 degree error in angle in or will result. Since .02 g is about .6 ft./ sec2, and typical AUV longitudinal speed variations can be bounded by something like 10 ft./sec, should be somewhat greater than 20 seconds from this consideration.

While Eq. 3 shows that the components of angular orientation obtained from the integral of the angular rate sensor signals are high-pass filtered, the same is not true of angular rate biases. Rather, referring to Figure 3, a bias value of must be countered by a steady state attitude estimation error of an amount, , where

The maximum output of the angular rate sensor is 50 deg/sec. If rate bias is 0.1 percent of this value, or 0.05 deg/sec, and is 100 sec, then, from the above equation, an attitude error of 5 degrees will occur. Clearly, this is unacceptable. A solution to this problem is to high-pass filter angular rate signals, or equivalently, estimate the bias in such signals. If the high-pass filter approach is taken, consideration of Eq. 3 and 4 shows that the effect on angle estimation will be small if this filter cutoff frequency is substantially below . Fortunately, this is an issue that can be investigated by bench testing. Specifically, the IMU can be inclined to a known angle and the angular rate sensor bias observed. The IMU can then be abruptly restored to a horizontal orientation, and transient and bias effects observed for various high-pass filter time constants. We intend to conduct this sort of experimental evaluation along with further error model development and simulation studies in parallel with our towfish data collection efforts.

Velocity Estimation

With regard to velocity estimation error, water speed should be measurable to an accuracy of 10 percent or better. If Euler angles are estimated to an average accuracy of one degree or so, then north and east acceleration will be in error by approximately 0.6 ft./sec2. This means that for this loop should be only a few seconds, and for longer times, velocity estimates will be dominated by water speed sensor errors. Of course, these numbers are only illustrative, and are used here mainly to show the importance of water speed sensors (or other velocity measuring means) for the class of inertial sensing instruments we have selected.

An attractive alternative to electromechanical water speed sensors is provided by doppler sonar. Such systems can accurately measure either velocity relative to the water column or (at low altitudes above the sea bottom) ground velocity [19]. It is also possible to obtain very precise ground velocity estimates from GPS during intervals in which these signals can be received [14]. Of course, this would not apply during submerged navigation, so use of GPS velocity estimates is limited in this case to weighted velocity reset, similar to the use of GPS position estimates in position reset. We are purchasing a doppler sonar for Phoenix [19], and may conduct additional towfish tests incorporating this unit.

Position Estimation

Unlike the Euler angle and velocity estimation filters, as can be seen on Figure 3, there is no continuous corrective feedback around the position estimating integrators. As noted previously, this is because when the receiver antenna is awash or periodically submerged, GPS fixes are available only intermittently. Thus, GPS signals are used for integrator reset as they become available. The weighting applied to a given fix in comparison to the integrator output is critically dependent on whether or not DGPS is available in a given operational scenario. From Figure 5, and the above discussion of velocity errors, when DGPS is available, it represents the most accurate position information available, and should be used to reset the position filter with unity gain. On the other hand, if DGPS is available during testing (as it always will be for our experiments), but not during operation (as in some military missions or in open ocean navigation to a work site), then DGPS can be taken as truth during system development and the best reset weighting for raw GPS can be determined experimentally. It should be noted that since raw GPS position estimation errors are typically an order of magnitude or more greater than DGPS errors, submergence times for this mode of navigation can be correspondingly increased in this case, amounting to a few minutes rather than tens of seconds.

Experimental Results

Since at the time of this writing we have no at-sea test data from our breadboard SANS, the above discussion is intended only to explain the methodology we intend to follow in determining values for the gain matrices Ki in Figure 3, and to make plausible our belief that this system will be useful for AUV navigation. Quantitative results on navigation accuracy will be made public as they become available in the AUV project pages of our World-Wide Web (WWW) site (http://www.cs.nps.navy.mil/research/auv).

SUMMARY AND CONCLUSIONS

We have described an experimental system currently under development for integrated GPS/INS navigation of AUVs in shallow water environments. This system (SANS) is of small physical size and relatively low cost. The components selected are of less than true inertial grade accuracy, so aided navigation employing water speed sensing is required. This means that accelerometers are used mainly to derive low frequency attitude information, and are not utilized for velocity or position estimation for periods longer than a few seconds. The availability of differential GPS in our open ocean test site allows us to experimentally choose navigation filter gains and to accurately assess overall system performance in a variety of sea states and for various operational scenarios. Much additional work is needed to develop appropriate error models and means of optimizing navigation filter gains for this class of systems. Nevertheless, this paper presents component test results and qualitative error estimates which support our belief that submerged navigation accuracy comparable to that of surfaced GPS fixes is attainable.

ACKNOWLEDGEMENTS

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