1995

Evaluation of an integrated GPS/INS system for shallow-water AUV navigation (SANS)

Bachmann, E.R.

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

E. R. Bachmann, R. B. McGhee, R. H. Whalen, R. Steven, R. G. Walker,
J.R. Clynch, A.J. Healey, X. P. Yun

Naval Postgraduate School, Monterey, CA 93943
E-mail: {bachmann, mcghee,whalenr}@cs.nps.navy.mil

Abstract

Many possible Autonomous Underwater Vehicle (AUV) missions require a high degree of navigational accuracy. The Global Positioning System (GPS) is capable of providing this accuracy. However, intermittent reception caused by either wave action or deliberate submergence will cause the loss of GPS position fix information for periods extending from several seconds to minutes. The SANS system is designed to demonstrate the feasibility of using a low-cost strapped-down Inertial Measurement Unit (IMU) to navigate between GPS fixes. It is anticipated that navigational accuracy comparable to GPS is possible between fixes.

Introduction

The SANS [1] is an experimental GPS/INS navigation system composed of low-cost components of small physical size. In final form, it is expected to be a self contained, internally or externally mountable package. It is designed for use on an AUV or any other vehicle conducting near-surface operations which can periodically conduct a "pop-up" maneuver in order to obtain a GPS position fix. Current plans call for installation of the SANS on board the NPS "Phoenix" AUV during the summer of this year.

The Phoenix is an experimental vehicle designed for research in support of shallow water mine countermeasures and monitoring of coastal environments[2]. Due the clandestine nature of the missions for which it is designed, and the requirement for the vehicle to submerge to investigate targets, the mounting of a mast to extend a GPS antenna above the effects of wave action is not considered desirable or practical. Therefore, any system relying solely upon GPS would not be sufficiently robust to provide accurate navigation information during surfaced or near surface operations due to intermittent reception. The SANS was designed as a method of solving this problem and allowing the Phoenix to navigate submerged during periods in-between GPS fixes.

This paper describes the hardware and software architectures of the current prototype of the SANS. It also documents the results obtained by both bench testing and at-sea evaluation of the system. The central component of the SANS is a twelve-state Kalman filter. The filter combines high and low frequency information in an approach usually referred to as *complementary* filtering. Tuning and calibration of this filter has focused primarily on investigation of the effects of variation of gains and scale factors and verification of design correctness. These tasks were accomplished through simulation, tilt-table testing and open water tests. Post-processing of all data played a key role in helping to properly tune the filter.

System Description

The major hardware and software components of the SANS system have changed little from those described in [3] and [4]. Replacement of the majority of the hardware components is anticipated within the current year. Most of the software objects will be transferred directly to the next system.

Hardware

Figure 1 shows a block diagram of the proof of concept GPS/INS hardware system. 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.

The major input devices to the system are a GPS receiver [5], an Inertial Measurement Unit or IMU [6], a magnetic compass [7], and a waterspeed sensor [8]. With the exception of GPS data, all inputs are externally filtered by an active analog anti-aliasing filter with a bandwidth of 10 Hz. This filter also converts the double sided analog output of the IMU into a single sided signal within the range of the A to D converter [9]. The values delivered by the A to D converter are multiplexed by the data logging computer [10] and stored in packets. Each packet contains eight measurements taken from the IMU, compass, and waterspeed sensor. The packets are transmitted via modem [11] to the main processing computer in the towing vessel at approximately 5 Hz.

The GPS receiver [5] which is operated in real-

0-7803-3185-0/96$5.00©1996 IEEE

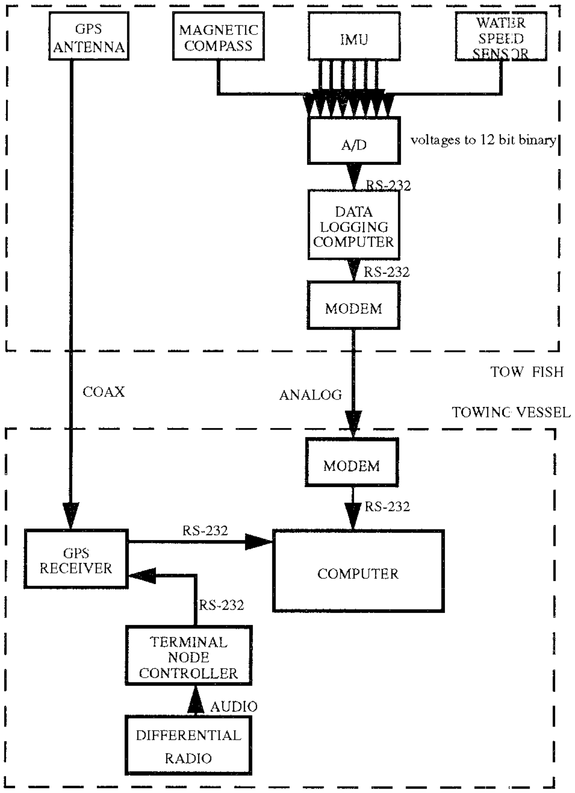

Figure 1: SANS proof of concept hardware.

time differential mode resides onboard the towing vessel along with the differential radio and the terminal node controller (TNC). Satellite information is received via coax cable from a GPS antenna mounted on top of the towfish. The Differential GPS (DGPS) position signal is feed directly into the main processing computer.

The IMU is a Systron Donner "MotionPak"[6]. It is a self contained unit which provides analog measurements in three orthogonal axes of both specific force (linear acceleration plus gravitational acceleration) and angular velocity. It consists of a cluster of three linear accelerometers and three "Gyrochip" angular rate sensors. Detailed analysis of the individual components of the SANS system can be found in [3] and [4].

Software

The purpose of the SANS software is to utilize IMU, heading, and water-speed information to implement an Inertial Navigation System (INS), and then integrate this with GPS information into a single system which produces continuously accurate navigational information in real time. The INS is implemented using Kalman filtering techniques in which differential GPS fixes are treated as 'error-free data' allowing periodic reinitialization of the INS to correct accumulated errors and develop error biases. All sensor data is logged in raw form for postmission processing.

Figure 2 is a data flow diagram for the SANS filter design. The twelve state variables are the outputs of each of the three integrator blocks, estimated current in north and east directions, and the bias estimates for the angular rate readings. The state variables are shown in Table 1. In Figure 2, R is a rotation matrix [12] and T is a body rate to Euler rate transformation matrix [13]. The major difference between the filter described in this paper and that in [3] and [4] regards the point in the filter process at which the apparent current $(\dot{x}_c, \dot{y}_c)$ error correction is made. In the previous version of the filter, the apparent current was added to the waterspeed $(\dot{x}_w, \dot{y}_w)$. The difference of this sum and the estimated north and east velocities $(\dot{x}_e, \dot{y}_e)$ was taken and fed into the north and east accelerations $(\ddot{x}_e, \ddot{y}_e)$ with a gain K_3. Due to the poor results obtained from initial sea tests in [3], this approach was suspected to cause the filter to be underdamped or even unstable.

Euler Angles	Φ, θ, ψ
North & East Velocity	$\dot{x}_e, \dot{y}_e$
North & East Position	x_e, y_e
Apparent Current	$\dot{x}_c, \dot{y}_c$
Angular Rate Bias Estimates	p_b, q_b, r_b

Table 1: State variables of the Kalman filter.

The ten continuous-time state components of the filter of Figure 2 consist of three Euler angles (Φ, θ, ψ), two horizontal velocities $(\dot{x}_e, \dot{y}_e)$, two horizontal positions (x_e, y_e) and three angular rate bias estimates(p_b, q_b, r_b). In the actual SANS digital filter implementation, the continuous-time integration is approximated by numerical integration. In this sense, the ten "continuous-time" state components are "discrete time" state values. This is necessary due to limitations placed on the minimum integration sampling times by the computer and A-D hardware characteristics. However, the two state components $(\dot{x}_c, \dot{y}_c)$ composed of apparent ocean current in the East and North directions are *inherently* discrete. That is, their discrete nature is due to diving and wave action which results in intermittent GPS signal reception. Thus, these two states are updated aperiodically, as is characteristic of discrete event dynamic systems [14]. This being the case, it is difficult to apply Kalman filter theory to obtain optimal time-varying values for the gain matrices K_i shown in this figure. Instead, constant gains were computed initially from bandwidth and steady-state error considerations [3,4] and subsequently adjusted based on the results of experimental studies.

The continuous state part of Figure 2 shows that the Euler angle and linear velocity outputs are fed back to the corresponding integrator inputs. Thus if the gain matrices K_1, K_2, and K_3 are all diagonal, each of these integrators is in fact a low pass filter for each of its inputs. This prevents unlimited growth of state estimates

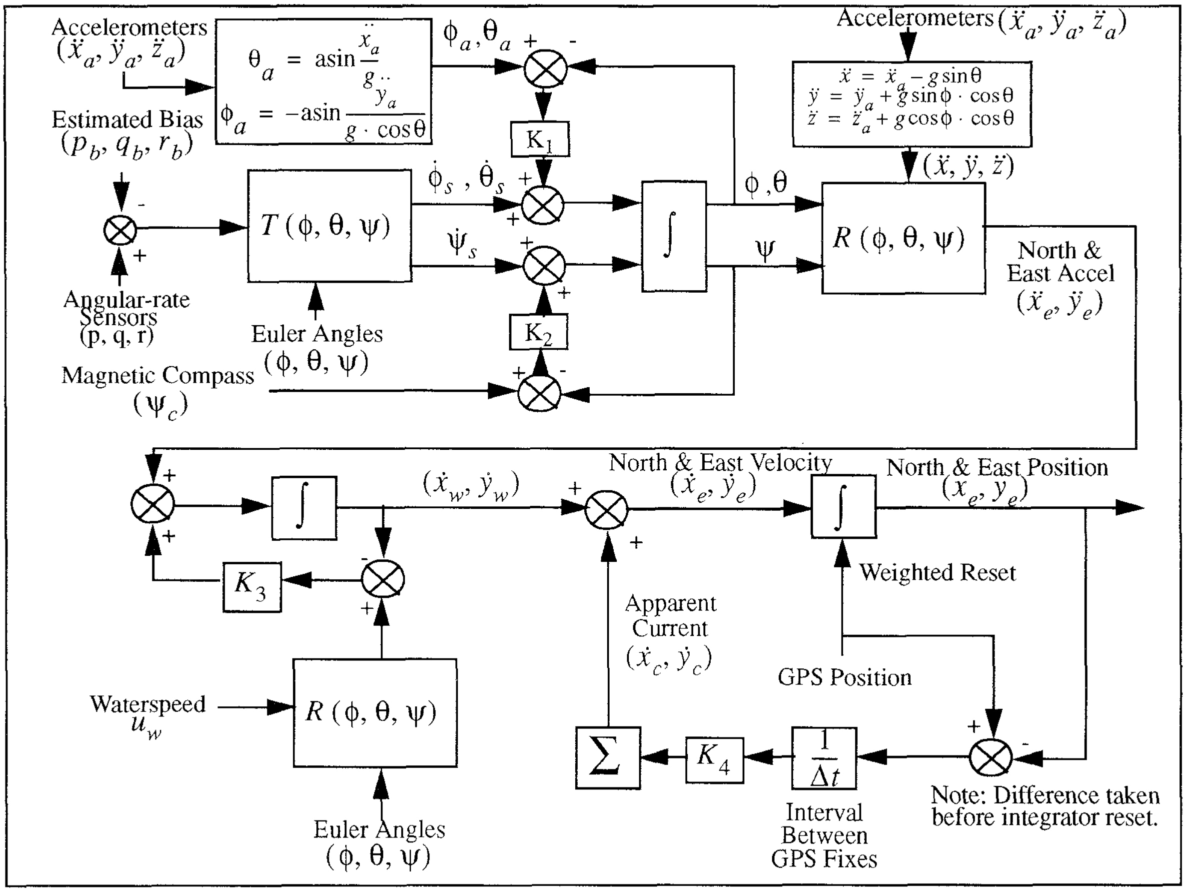

Figure 2: Twelve-state velocity-aided navigation filter.

in the presence of unmodeled bias errors in state derivative inputs to integrators. Each integrator is also furnished with an independent source of low frequency information to correct for long-term decay of state estimates resulting from this feedback[4].

The sources of low frequency information include the accelerations sensed by the accelerometers ($\ddot{x}_a$, $\ddot{y}_a$, $\ddot{z}_a$), the magnetic compass readings (Ψ_c) and the water-speed (u_w). The accelerometer data in this case is utilized in a manner similar to inclinometer readings. This provides information regarding how much of the specific force felt in each axis is due to gravity.

In addition to filtering, the IMU acceleration readings require other correction or conversion. Computed gravity is subtracted from specific force readings of the accelerometers to transform them into the accelerations $\ddot{x}$, $\ddot{y}$, $\ddot{z}$ prior to rotation to $\ddot{x}_e$, $\ddot{y}_e$, $\ddot{z}_e$. See [15] for a detailed mathematical derivation of all aspects of the SANS filter design.

Testing and Calibration

Testing and calibration of the SANS filter was conducted in three phases. The purpose of these phases was to prove the correctness of the filter design and implementation, to determine reasonable values for the filter gain matrices and scale factors, and to evaluate overall system performance during open-water tests. The major goal of the tests was to further evaluate the feasibility of the entire SANS concept and determine where primary emphasis should be placed in the next major development steps.

Simulation

In order to verify the correctness of the filter design and implementation, a simulation was constructed in LISP using the same filter design as that implemented in the actual SANS software [16]. The basic purpose of this verification was to insure that both the simulation and the actual SANS code produced the same position estimates given the same input. The verification process proceeded in two steps.

In the first step, the simulation was fed a trajectory list specifying predetermined course, speed and depth commands to be carried during a simulated mission. A simulated AUV followed these commands and carried out the mission. While the mission progressed, a *mission-data* file was generated which contains accelerometer, ($\ddot{x}_a$, $\ddot{y}_a$, $\ddot{z}_a$), angular rate (p, q, r),

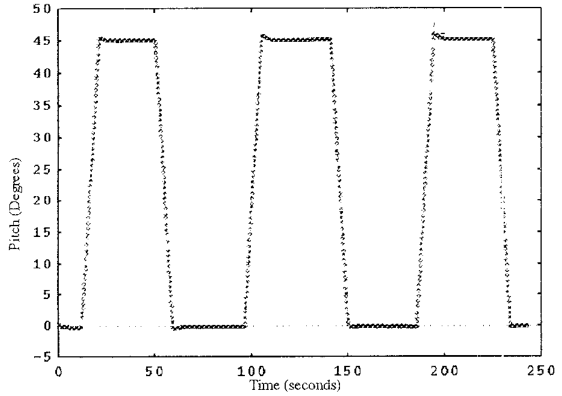

Figure 3: 45 degree pitch excursions at 5 degrees per second.

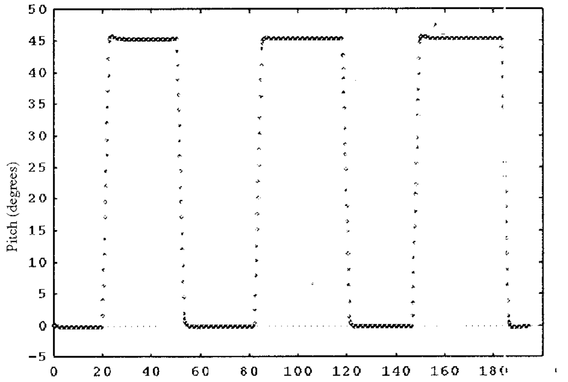

Figure 4: 45 degree pitch excursions at 15 degrees per second.

waterspeed (speed through the water), and heading values at tenth of a second intervals. In the second step of the verification process, the *mission-data* file information was fed into each version of the navigation filter. The performance of the filters was then evaluated by comparing 'actual' position of the simulated vehicle with the estimated positions as determined by the two filters.

The results of this evaluation show that the LISP filter and the real-time and post-processing software (the latter two written in C++) give essentially identical results [16]. This provides considerable assurance that the computations of Figure 2 have been correctly coded.

Static Testing

Due to the aperiodic nature of the SANS filter and a lack of statistical data on errors in the data sensed by the towfish, determination of satisfactory values for the gain matrices and proper scale factors for the input data has proved difficult [3]. Consequently, in order to be able to precisely control input to the filter, the SANS unit was placed on a Haas rotary tilt table, Model TRT-7[17]. The table has two degrees of freedom (DOF) and is capable of positioning to an accuracy of 0.001 degrees at rates ranging from 0.001 to 80 degrees/second.

Tuning data for the SANS was obtained by moving the SANS unit through each DOF at varying rates within a 45 degree range. The attitude as determined by the SANS was then plotted and compared with the actual motion of the unit. Through this comparison, it was possible to determine initial gain values and scale factors. The tilt table data was then post-processed using these initial values and once again compared to the actual motion of the SANS unit. This process was repeated several times until the attitude determined by the filter 'matched' the true motion of the unit.

Figure 3 is an example of the results obtained during the tuning process. The slight overshoots following each motion may indicate the scale factor for the y axis angular rate sensor is slightly high. However, this effect may also be due to undersampling problems. The flatness of the curve following stabilization after each motion indicates that a reasonable gain value has been determined as does the distance between the tails of each step.

Figure 4 demonstrates the limitations placed on the SANS unit by the current 5 Hz sample rate. The presence of both under and overshoots indicates the motion stopped somewhere in-between widely spaced samples. In each case however, the use of low frequency acceleration data appears to have allowed the SANS to regain an accurate attitude estimate within the time constant, $\tau = 1/K_1$, of the complementary filter (Figure 2).

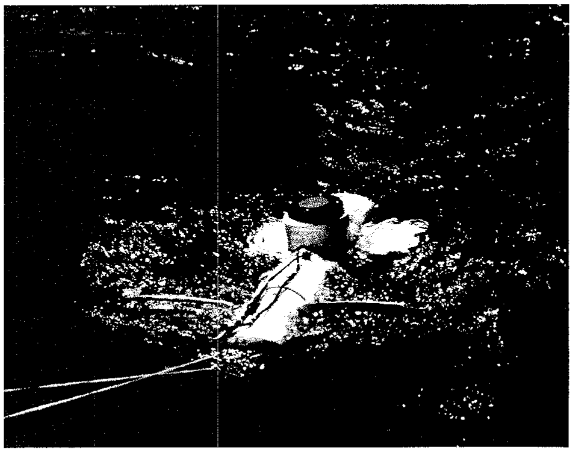

Figure 5: Towfish testing of the SANS system.

At-Sea Testing

At-sea performance evaluation was made by repeatedly traversing a triangular course in Monterey bay. The vehicle or towfish was the same unit described in [3] with the exception of minor control surface modifications made to improve control and dive characteristics. Figure 5 shows the towfish during tests in Monterey Bay. The GPS antenna on the towfish was connected to the receiver on the boat via 60 feet of RG-213 coaxial cable where it was combined with the differential correction information being broadcast by the Monterey

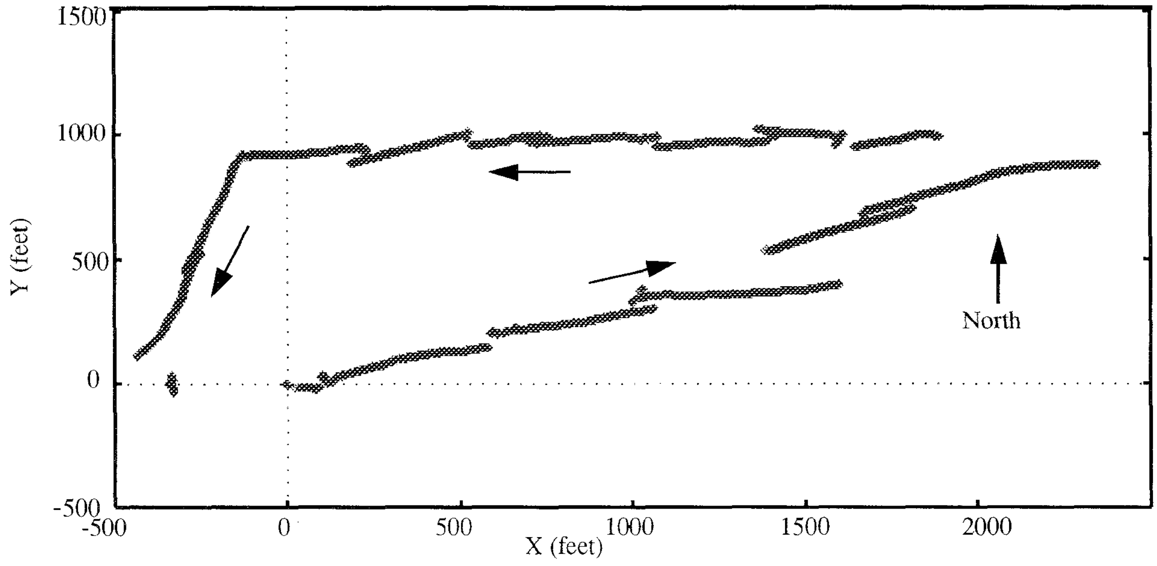

Figure 6: Position plot obtained during operation with submerged periods of 30 seconds.

Bay Research Institute (MBARI) using a Trimble RL base station at a distance of approximately 3 km. The eight channels of information sampled by the A to D unit were transmitted via modem over 100 feet of RG-58 cable. The computer provided a real-time navigation solution throughout the test runs. Each circuit of the course required approximately 20 minutes and constituted a separate data set. Four data sets were obtained.

The first traversal of the course was conducted with the towfish on the surface. Thus, during this run, DGPS position information was continuously available. This established a basis for subsequent runs and provided data which could be used to calibrate the water-speed sensor during post-processing. During the remaining runs, the towfish was submerged for periods of either 30 or 60 seconds. Following each submergence, the towfish was left on the surface for intervals of approximately five to seven seconds during which the SANS obtained three to five DGPS fixes.

The data depicted in Figures 6 - 11 was collected during the third full traversal of the triangular course. The gain matrices K_1, K_2, K_3 and K_4 were set to 0.6, 0.6, 0.5 and 0.5 respectively. Figure 6 shows the grid positions estimated by the SANS filter. The origin of the grid is the starting point for the run. All turns were made to port. The segmented nature of the plot is due to the repeated dives of the towfish. Each segment represents a period of below surface operation of approximately 30 seconds. As is to be expected, the position estimates made by the SANS tended to degrade during these times due to the accumulation of dead reckoning errors. Each time the towfish surfaced, the SANS unit was able acquire a DGPS fix, and determine its true position and update the apparent current estimate. The starting points of each segment can therefore be interpreted as actual positions (within an accuracy of approximately 1 m. rms [4]) and the distance from them to the end of the previous segment the position error prior to surfacing. The average error during each segment can be estimated to be one half the maximum position error which occurs just prior to obtaining a DGPS update.

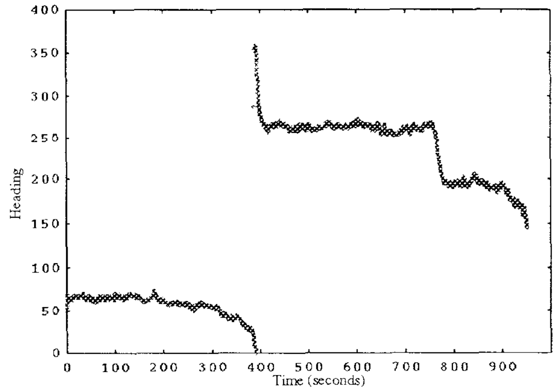

Figure 7: Compass heading during at-sea testing.

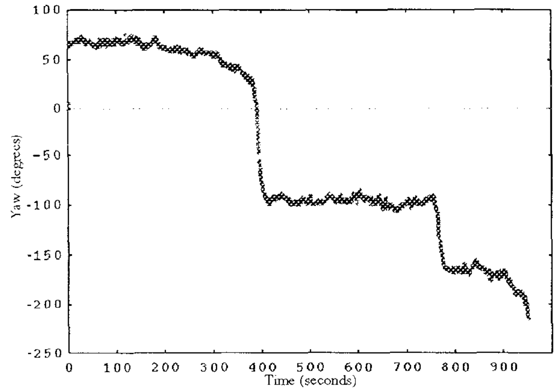

Figure 8: Yaw attitude during at-sea testing.

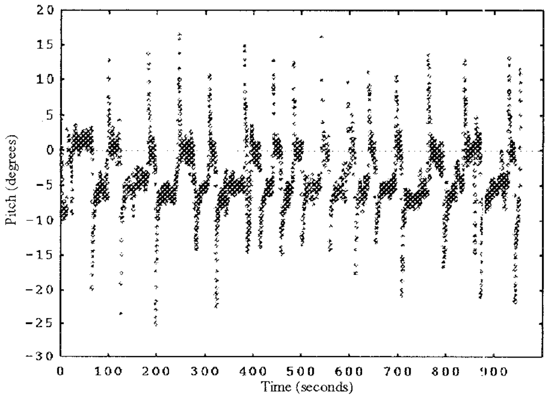

Figure 9: Pitch attitude during at-sea testing.

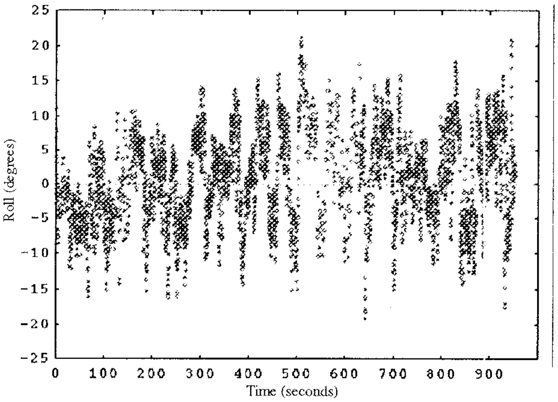

Figure 10: Roll attitude during at-sea testing.

Detailed examination of Figure 6 finds significant errors in the middle of the first leg and following the first turn. On the second and third legs however, the errors become much smaller. On average, during this period of operation, the Root Sum Squared (RSS) error is estimated to be 10.2 meters. Based upon these observations, it becomes apparent that during the first leg of the course, the apparent current estimates made by the Kalman filter (Figure 1) were not yet accurate. However, after approximately 400 seconds of operation, just before beginning the second leg, the towfish completed the sixth surfacing providing the filter with the sixth set of DGPS fixes. At any point in the run, the fraction of total current estimated, G, is given by (1), where n is the number of DGPS fixes obtained. Thus in an idealized situation, with K_4 set to 0.5 and six position corrections obtained, the amount of system error and water current corrected for should have been approaching 100%.

$$G = 1 - (1 - K_4)^n \qquad (1)$$

Figures 7 - 10 show the ability of the filter to determine the attitude of the SANS. Figure 7 displays the compass heading of the SANS versus time. Comparison of Figure 7 to Figure 6 shows a strong correlation. Figure 8 displays the yaw attitude as calculated by the filter. Note that filter heading does not make a 'branch cut' at 360 degrees and becomes negative after passing through North in a left hand turn. If the towfish were to make circles in a counter clockwise direction, the filter heading would continue to grow in the negative direction until a right-hand (clockwise) turn was made. This is necessary to avoid artificial discontinuties to the heading estimation filter, which would otherwise cause serious transient errors to propagate through the filter. That is, the filter output and the compass output are in agreement provided the comparison is made modulo 360 degrees. Figure 9 shows the pitch attitude of the SANS unit throughout the run. The alternating nose down and nose up pattern makes it simple to identify the beginning of each period of submergence as well as the beginnings of climbs to bring the towfish back to the surface. Figure 10 shows that the roll attitude of the SANS was centered around zero but varied widely as was visually observed during the test run. Excessive rolls (above 45 degrees) and/or lateral accelerations may cause the magnetic compass to provide erroneous heading information [16].

Figure 11 shows the waterspeed over the course of the test run. The speed averages approximately 5 fps or 3 knots. This also correlates well with Figure 6. The course as plotted was estimated to be 5,300 ft. in length. Given course completion in just under 950 seconds, the actual speed was approximately 5.5 fps or 3.3 knots.

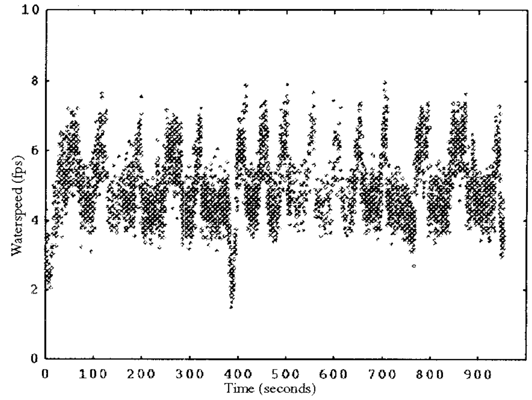

Figure 11: Waterspeed during at-sea testing.

Future Work

Plans for the immediate future call for replacement of the majority of the hardware components currently being used in prototype and construction of a more compact unit which will allow all components to be placed in the towfish. This unit will be entirely contained in a single container not more than 120 cubic inches in volume. Other than compactness, the primary advantage of this improved system will be an increase in sampling rate of approximately 100 fold, and improved processor capability to handle the larger volume of data. The improved system will include a more accurate 3-axis magnetometer rather than a gimballed 2-axis compass system [16] currently in use. The current paddle-wheel waterspeed sensor will also be replaced by a more accurate turbine flow type. In final form, the system will

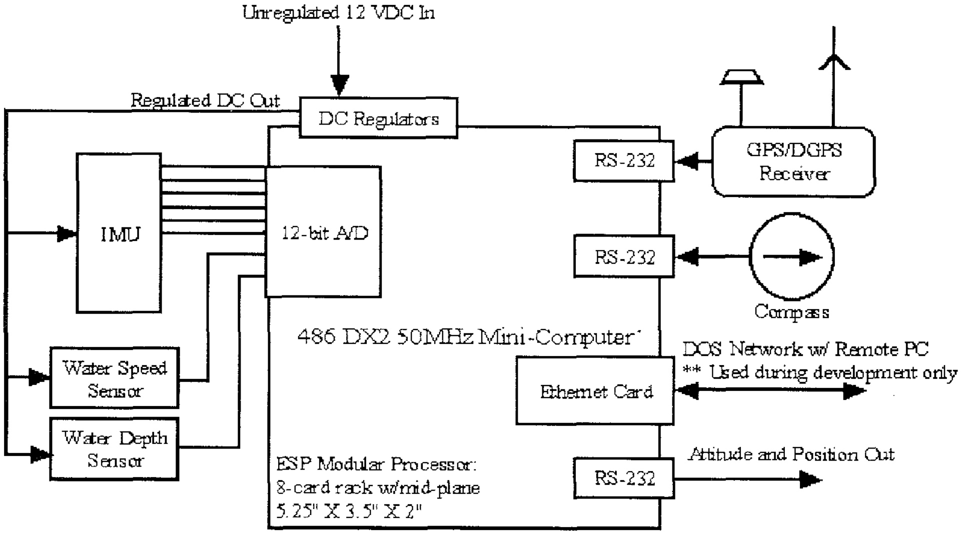

Figure 12: Block diagram of future SANS hardware configuration.

be water-tight and connection will be required only for power, position and attitude output and DGPS antennas. Figure 12 is a block diagram of a proposed upgraded SANS hardware configuration [18].

Modifications to the Kalman filter design (Figure 1) are planned that will allow compensation for centripetal acceleration during turns[15]. Work also still remains to be done to complete tuning of the filter. This work will require more exhaustive tilt-table tests once the new hardware configuration has been assembled as well as further simulation studies before more at-sea testing is undertaken or the SANS is installed onboard the NPS Phoenix.

Conclusions

Although, it has not yet been demonstrated, the test and simulations described in this paper suggest that it is possible to navigate with 10 meter rms accuracy for periods of up to one minute in-between DGPS position fixes using a low-cost IMU. The preliminary filter design process is felt to be largely complete. Further testing is required however to find better values for gain matrices and to compensate for possible transient loss of differential capability by the GPS receiver.

The low data rate of the current system appears to be its major limitation. This problem will be eliminated by reconstructing the SANS and placing all components in a single compact container.

Acknowledgments

This research was supported in part by the National Science Foundation under Grant BCS-9306252 to the Naval Postgraduate School.

References

[1] Kwak, S.H., et al., "An Experimental Investigation of GPS/INS Integration for Small AUV Navigation", *Proc. of 8th Int'l. Symp. on Unmanned Untethered Submersible Technology*, Univ. of New Hampshire, Durham, NH, September, 1993.

[2] Healey, A.J., et al., "Evaluation of the NPS PHOENIX Autonomous Underwater Vehicle Hybrid Control System", *Proc. of ACC'95 Conf.*, Seattle, WA, June, 1995.

[3] Bachmann, E.R. and Gay, D.L., *Design and Evaluation of an Integrated GPS/INS System for Shallow-Water AUV Navigation*, M.S. thesis, Naval Postgraduate School, Monterey, CA 93943, September, 1995.

[4] McGhee, R.B., et al., "An Experimental Study of an Integrated GPS/INS System for Shallow-Water AUV Navigation (SANS), *Proceedings of the Ninth International Symposium on Unmanned Untethered Submersible Technology (UUST)*, September 25-27 1995, Durham, NH. pp. 153-167.

[5] Anon., *Motorola PVT6 GPS Receiver*, Motorola, Inc., Phoenix, AZ, 1994.

[6] Anon., *Systron Donner Model MP-GCCCQAAB MotionPak IMU*, Systron Donner, Inc., Concord, CA.

[7] Anon., *C-100 Electronic Compass*, KVH Industries, Inc., Middletown, RI, April 1992.

[8] Anon., *MK 11 Knotmeter*, Signet Scientific Co., El Monte, CA.

[9] Anon., *LTC-1290 A-D Converter*, Linear Technology Corp., Milpitas, CA.

[10] Anon., *Tattletale Model 5F-LCD Data Logger*, Onset Corp., Pocasset, MA.

[11] Anon., *Practical Peripherals PM14400FX Pocket Modem*, Practical Peripherals, Inc., Thousand Oaks, CA.

[12] Craig, J.J., *Introduction to Robotics*, Addison-Wesley Publishing Company, Reading, Massachusetts, 1989.

[13] McGhee, R.B. and Frank, A.A., "Some Considerations Relating to the Design of Autopilots for Legged Vehicles", *Journal of Terramechanics*, Vol. 6, No. 1, 1969.

[14] Ramadge, R. and Wohnam, W.M., "The Control of Discrete Event Systems", *Proc. of IEEE*, Vol. 77, No. 1, January, 1989.

[15] McGhee, R.B., *CS4910 Lecture Notes: Derivation of SANS Filter Equations*, Naval Postgraduate School, February 1996.

[16] Steven, R., *Simulation-Based Validation of Navigation Filter Software for a Shallow Water AUV Navigation System (SANS)*, M.S. thesis, Naval Postgraduate School, Monterey, CA 93943, March., 1996.

[17] Anon., *Model TRT-7 Tilting Rotary Table*, Hass Automation, Inc., Chatsworth, CA, July 1992.

[18] Walker, R. G., *Design and Evaluation of an Integrated, Self-Contained GPS/INS System for Shallow-Water AUV Navigation (SANS)*, M.S. thesis, Naval Postgraduate School, Monterey, CA 93943, June 1996.