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INCORPORATION OF GLOBAL POSITIONING SYSTEM INTO AUTONOMOUS UNDERWATER VEHICLE NAVIGATION

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Abstract

Navigation of an Autonomous Underwater Vehicle (AUV) is a problem that has not been adequately solved. Many methods of navigation of AUVs have been proposed and in some cases implemented. These have included the use of: gravity fields, sonar, and dead reckoning in conjunction with inertial navigation systems.

Although inclusion of the Global Positioning System (GPS) into AUV navigation has been briefly examined before, this possibility should be explored further by the AUV community. GPS is a series of navigational satellites that provide world-wide positioning, altitude, course, and speed information. In fact, GPS provides the most accurate open ocean positioning information available.

Even though an AUV navigating with GPS has the disadvantage that it must surface or at least extend its GPS antenna into the air to obtain a GPS fix, this method is still worth employing in many applications such as shallow water operations and long range transits. GPS could also be coupled with other short range mission specific navigational methods for application in various stages of a mission. GPS may also provide an excellent method of determining the position of an object of interest. When an object of interest is located, a GPS fix may be taken at that time or the last GPS fix may be used to accurately record the position of the object. Inertial and other sensors might be used to carry the GPS position to the object of interest.

Off the self components and GPS single board receivers provide a way to build the small, low power systems required for AUV incorporation. Given the accuracy of GPS, its proven performance, small size and low power, a GPS navigational based system offers many advantages to AUV navigation and may solve the navigational problem for many AUV applications.

Introduction

This paper will provide a brief introduction to GPS in general. In addition, the issues of incorporating GPS into AUV navigation will be explored. Test results conducted on a stationary GPS receiver will be analyzed for suitability in AUV navigation. In addition, a system design that Naval Postgraduate School is now pursuing to incorporate GPS into AUV navigation will be presented.

Navigation of AUVS

Most of the previous approaches to navigating of AUVs fall into two different categories: sensor based navigation and external signal based navigation. Sensor based navigation refers to an AUV navigational system that is self contained, using only data collected in real time by onboard senors and/or pre-stored information. These sensors provide information about the natural environment around an AUV. The most common sensors for sensor based navigation are sonar and vision sensors.

Sonar systems are primarily used in one of two ways: guidance sonars and speed measuring sonars. In order to effectively use a sonar guidance system, significant a priori knowledge of the environment is required. Basically, the AUV on board computer attempts to match the sonar information to stored geographical data in a terrain guidance or natural boundaries [1] method to determine its position. The same approach and a priori knowledge requirements applies to vision guidance systems. Speed measuring sonars include correlation and doppler sonar [2]. Here, the sonar determines the AUV speed via a ground locked mode, and this information is used to aid in dead reckoning. The reason for the use of sonar in determining speed is that it will provide AUV speed relative to the earth. Other methods such as propeller speed measurements and water speed measurements are affected by such factors as currents.

Another sensor based navigation method that requires a priori knowledge is a Gravity Gradiometer Navigation System (GGNS) [3]. This system uses gravity gradient sensors. The measured gravity gradients are compared with mapped values to determine AUV position.

Once the information from the sensors has been processed, it then may be used to assist an inertial navigational system (INS). Of the two types of inertial navigational systems, stable platform and strap down, only strap down provides a viable option for typical small AUV employment. Stable platform systems are generally too large and require too much power to be reasonably employed in AUVs.

External signal based components receive some type of external navigational signal not natural to the AUV environment. Such systems may include radio beacons, sonar beacons, transponders, Loran, Omega, Navsat, and of course GPS.

Sonar beacons, radio beacons and transponder trackers rely on close range transmitters. These transmitters must be in place before the AUV mission or put in place by the AUV. These are only good for short range navigation.

Loran and Omega are long range radio navigation systems. The major disadvantage of the Loran system is that it does not provide worldwide coverage. Although Omega [4] does provide worldwide coverage, it has undesirable characteristics for AUV employment. If the signal reception is interrupted, the Omega receiver has to be reinitialized. This makes it undesirable for AUV employment due to loss of signal when submerged and due to power drain. In addition, the best accuracy Omega offers is one to two nautical miles in its worldwide coverage. Navsat [5] is a

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satellite based navigation system that will be turned off sometime shortly after GPS 3-D worldwide coverage is complete. It provides fixes only every few hours. Loran is not expected to continue much past the year 2000 [6]. Omega will become a backup system for GPS. The preferred external navigational component that is worth developing into mission employment of AUVs is GPS.

Which of the sensor based navigational components to employ for AUV navigation depends on many factors including the size of the AUV, power availability, area of mission employment, operating depth, and transit distance. Of course, more than one of the sensors described above may be employed in an AUV navigational system. The sensors, in many cases, are not mutually exclusive to each other or to GPS. However, no single sensor discussed can match the accuracy of GPS, which is on the order of 100 meters anytime, anywhere. Using a reference station can reduce GPS errors by at least a factor of ten [7]. Although the inclusion of Global Positioning System (GPS) into AUV navigation has been briefly examined before [2], this possibility should be explored further by the AUV community.

GPS

The Global Positioning System (GPS) [8,9] is a satellite based navigational system that provides the most accurate open ocean navigation available. When completed, GPS will consist of a constellation of 24 satellites. Each satellite will be placed in high earth orbit (approximately 10,900 miles), which gives the satellites a period of 12 hours. Observing four or more satellites provides position and velocity in all three directions. By observing three satellites, two dimensional position and velocity may be computed. Currently the GPS constellation contains 16 satellites and the complete constellation should be in place by 1993. At that time, at least four satellites will be continuously observable from anywhere on the surface of the earth. Thus, world wide three dimensional coverage will be available. World wide two dimensional coverage is now essentially available.

GPS navigation is based on satellite ranging. Basically, the distance from the location on earth to a satellite is measured.The GPS system determines distances by timing how long it takes a signal from a GPS satellite to reach a receiver. This is accomplished by having the receivers and satellites both produce the same set of digital codes. Upon receiving the GPS signal, the receiver compares it to its own code and uses the offset between the two codes to determine the time it took for the signal to travel from the satellite. Multiplying this time of flight by the speed of light gives the distance to the satellite. Four satellites are required for a 3-D fix because the receiver clock error must be determined. Three satellites can be used to find a 2-D position if altitude is known.

The distance between a GPS satellite and a receiver is not enough to determine the location of the receiver; it has to know, as well, the position of the GPS satellite. To determine the position of a satellite in real time, the satellite broadcasts parameters of a model of its motion. This is called the "broadcast ephemeris". Each broadcast ephemeris is only good for navigation for a few hours (nominally six hours). The ephemeris must be obtained from each satellite as it rises to use its data in a real time solution. As a result, a GPS antenna must be exposed for a period of 30 seconds to 60 seconds once every few hours to update the ephemeris data.

GPS signals are very low power spread spectrum signals. The signal is generated by modulating a pseudo-random sequence of +/ - 1's onto a carrier. The Department of Defense (DoD) can control access to the system by altering the codes. Currently, there are two main forms of the pseudo-random codes: the Clear Acquisition (C/ A) code and the Precise (P) code. The C/A code is for civilian use, whereas the P code can be encrypted for only military use. The accuracy may be degraded by the DoD through Selective Availability (S/A). S/A creates a random clock error in the satellites, denying accurate use of GPS to all but those receivers with the cryptographic capability. Use of the P code, and removal of S/A, when encrypted, is available only to authorized military users.

GPS signals are broadcast in two main frequencies. The second frequency is used to remove propagation effects of the ionosphere from the ranges. These can be up to 30 meters. Because the C/A code is present on only one of two frequencies, use of a C/A only system leaves this ionospheric error in a navigation solution. However, it can be effectively removed for ranges up to a few hundred miles using a reference station [10]. The lack of an ionospheric correction is the major operational difference between C/A and P code receivers.

By DoD policy, S/A is on at a level that allows the GPS code to provide a horizontal accuracy of 100 meters (two standard deviations) in real time. With the use of a reference station the accuracy provided by both the C/A code and the P-code can be greatly improved. Table 1 provides a summary of expected accuracy. As it can be seen the status of whether S/A is on or off can greatly affect the accuracy provided by a stand alone GPS system.

TABLE 1: Positioning Accuracy of GPS

	S/A on	S/A off
Stand Alone	100 meters	16 meters
Differential	2 - 4 meters	2 - 4 meters

GPS positioning solutions may be classified in several different ways including: real time or post processing, static or dynamic, and absolute position or relative position. Real time solutions may be derived directly from a single receiver or differentially from two or more receivers. A differential solution involves placing a receiver at a known location. Another similar receiver is placed at an unknown location. A GPS fix is taken at the known location and the error in measurements or error in the position between the GPS fix and the known location may be applied to the receiver at an unknown location. This technique may be applied in real time, requiring communication between the receivers, or at a latter time in a post processing phase. Differential GPS may also be used in both a static mode (a stationary platform) and in a dynamic mode (a moving platform). Relative GPS simply means determining the relative position of one receiver in relation to another.

Obviously, what is important to the end user is his position. Although a military receiver can provide greater real time, stand alone accuracy, it requires crypto keys and proper authorization. As a result, the rest of this paper will only be concerned with civilian navigation receivers. This usually implies C/A code, single frequency receivers.

A GPS receiver may be continuous or switching. A continuous-tracking receiver has four or more dedicated hardware channels. Each channel tracks a single satellite and the satellite signal is continuously available. In a switching receiver one (or very few) hardware channels are available. Each channel samples two or more satellite signals. The switching involved in a receiver of less than four channels limits the accuracy of the dynamic positioning information because the satellite signals are not being received and processed at the same time. Due to the development of VLSI technology with multiple channels, five to 12 multichannel receivers will dominate this market. Therefore only multichannel receivers will be discussed. Although only four tracked satellites are needed to provide a 3-D position solution, the more satellite signals that are received and processed in real time, the quicker and more accurate is the solution provided.

One aspect that makes the use of GPS in AUV navigation possible is the advent of single board GPS receivers or engines. These are small, low weight, and in general low power. In addition, GPS engines are highly capable. GPS engines are available from at least five manufacturers [11]. With a single board GPS engine, the user will have to supply the power and the interface. The interface, in most cases would be a standard RS 232/422 interface which should present little or no problem in interfacing with the AUV mission or navigation system computer. The cost of these single board GPS engines varies with the complexity and capability of the receiver but in general runs from $500 to $3,000.

Issues of GPS use in AUV Navigation

As stated in the previous section, the important concerns of size, weight, and to some extent, power requirements of GPS receiver employment in AUV navigation has been answered by the advent of single board GPS receivers or engines. However, other concerns have not been answered yet, and some of them may not have complete answers other than incorporating the constraints of using GPS into AUV mission planning.

The main concern of GPS employment in AUV navigation is that GPS signals have no water penetrating capability. Therefore, to receive the signals, an antenna associated with an AUV employing a GPS system must be clear and free of the water. There are three possible antenna configurations to meet this requirement. These are fixed, retractable, or expendable antennas. A fixed antenna is non-moving antenna placed on the outside of the AUV. The AUV would have to surface to expose this antenna and stay surfaced until the required information had been received and processed adequately. A retractable antenna is one that the AUV would deploy while still submerged. When the required information is received, the antenna is retracted back to the AUV. The expendable antenna would work along the same principle as the retractable antenna except that it would be used once and jettisoned. When required, another antenna would be deployed and again jettisoned. This requirement to expose a GPS antenna clear and free of the water is the greatest disadvantage of employing a GPS system in AUV navigation.

In addition to exposing an antenna, another key concern is GPS system power consumption. It is quite obvious that AUVs have limited amounts of power. Although GPS engines are, in general, low power, these engines can present a significant power drain if continually powered up. One solution would be to have the AUV mission computer turn on the GPS system only when GPS signals were required and to turn off the system when GPS signal reception was not required. In order for this approach to be successfully employed, fast power up, set up, acquisition and solution time GPS engines are required. It could be mission degrading if the AUV had to surface for a long period of time for the GPS system to acquire the satellites and provide positioning information. The more time the AUV spends getting a GPS fix, the less time it spends on the primary mission and the less power it has available to expend on its primary mission. Therefore, for the purposes of GPS employment into AUV navigation, required antenna exposure time should be minimized. Our current work has a goal of thirty seconds or less.

There are two antenna exposure time issues. The first is acquisition time, and the second is solution time. Acquisition time refers to the time it takes for the GPS system to acquire a minimum number of acceptable satellite signals. In no case would this number be lower than three signals. Four or more satellite signals would clearly improve the results provided by the GPS system. If the information from the GPS system is to be used only in post processing of mission data, then satellite signal acquisition time is the important time constraint. If a GPS solution is required real time, then the solution time becomes an important time constraint. Generally speaking, the real time GPS solution fix will take more time.While these two times could be made small with appropriate receiver firmware, most receivers are not designed for infrequent satellite data. The solution time can be considerable longer than satellite acquisition time. This is dependent on receiver type. For post processing this is not a problem.

The time to acquire satellites and find a fix is a function of many variables. In order to acquire a satellite and make measurements the receiver must find the signal in a two dimensional space, range and Doppler shift. For most inexpensive receivers, the Doppler space search dominates. This is due to the quality of the oscillators that can be used in this class of receivers. However, some receivers, like the receiver selected for this test, advertise rapid acquisition due to a proprietary method of keeping track of the receiver oscillator drift to increase their performance.

In order to obtain a fix, and in some cases improve acquisition times, a receiver must have an ephemeris for each satellite it uses. This takes a minimum of 18 seconds of tracking, and normally takes 30 seconds or more. This can significantly delay the use of data from a satellite that previously has not been tracked long enough to obtain an ephemeris.

Another important consideration is the design of the receiver logic. In some receivers there are "sanity tests". These tests tell the receiver that something is wrong if it has not had a solution or measurement for some period of time. The receiver then ignores its stored information and begins searching at a more primitive level. This is not the case for the receiver tested here, but will be important to the use of some receivers in AUVs.

The main reason that GPS represents an attractive approach for AUV navigation is the position accuracy GPS is capable of providing despite the disadvantages associated with antenna exposure. As mentioned before, GPS real time accuracy during an AUV mission would be around 100 meters. With the use of post processing, the accuracy obtainable approaches two meters.

An important point that needs to be made is that GPS need not be the only navigation method employed or even the primary one. When and how to employ a GPS based navigational system into AUVs is clearly determined by the mission of the AUV. GPS may play a small supporting role in deep submergence AUVs where frequent surfacing over the duration of the mission is not possible. In this case, GPS initializes an INS or other navigational systems before the deep submergence AUV commences the mission. GPS can also assist the deep submergence AUV by determining and verifying its location when it does surface. GPS may play the primary navigating role in shallow water AUVs and shallow water missions where extending or exposing an antenna is much more acceptable. Another role GPS would play very well would be to be used for navigating an AUV on a long transit due to the real time accuracy provided by GPS.

The real time position information is provided to the AUV navigation system or mission computer for immediate use, whereas the non-real time or post processing use of GPS requires analysis after the mission is complete. One use for the post processing method would be object location. If the AUV found an object of interest, it would expose an antenna, obtain satellite signals, and then continue on its mission. The information recorded would then be processed after the AUV has returned and the location of the object would be determined.

Test Results

General Comments. Due to cost and availability, only commercially available, off the shelf, GPS receivers were considered for the work presented in this paper. An initial look at available receivers showed the Globos LN 2000 F SEL (SEL) receiver to be very promising for AUV employment because of the advertised fast satellite acquisition times. This SEL receiver is a C/A code, six channel, single frequency receiver. This receiver was put through extensive tests. The purpose of these tests was both to evaluate this specific receiver and the feasibility of incorporating GPS receivers, in general, into AUV navigation.

The test methodology was designed to test the receiver in three areas. The first area tested was concerned with how long it took the receiver to acquire three satellites and then four satellites. This type of test shows whether a receiver can be utilized to collect satellite data for post processing. Acquiring three satellites will be a minimum for this purpose because the GPS signals will be collected at sea level, but four or more satellites will provide a better positional accuracy. The second testing area was to determine how long it takes the receiver to provide a valid real time navigational solution. The third area to be evaluated is how accurate the navigational solutions were.

Procedure. During the tests the standard SEL display unit was not used. Instead, a junction box was built that allowed the GPS receiver to communicate with a computer via the RS 232 port. This GPS receiver had several modes that could be selected. The mode selected determined the type of information provided as well as the baud rate, parity, number of data and stop bits for the selected mode. The different types of information that could be provided include the PVT (Position, Velocity, Time) message, NMEA 0183A (National Marine Equipment Association) message, Nav String (Navigation String) message, and the Raw Satellite data message. The Nav String data was used for this study. This data contains the position, a figure of merit, a list of the satellites tracked, and the signal to noise ratio on each satellite.

The antenna for the GPS engine was placed above all obstacles in the immediate area to limit the possible introduction of multipath errors. Mutipath errors are GPS satellite signals that are reflected from a surface and then received by the receiver.

Given the nature of AUV operational employment, an important consideration for a GPS receiver evaluation is its operational characteristics with intermittent power supply. The basic test methodology consisted of a simulated periodic surfacing of an AUV. This was accomplished by turning the power on for the GPS engine for a simulated surfacing and turning the power off for a simulated submerging. The surfaced time period was set at 0.5 minutes for the purpose of these tests. The simulated submergence times (power off times) consisted of 0.5 minutes, one minute, two minutes, four minutes, and eight minutes. Ten simulated surfacings were done per test run. There were three or four test runs (30 - 40 observations) for all cases except for the eight minute off case for which there were two runs.

This testing methodology was used to determine how long the receiver could go without receiving signals and produce acceptable satellite acquisition and navigational solution times. At some off time there should be a break point (a power off time) that is too long for the receiver to consistently provide the information required in an acceptable surfaced time (on time) period. During the gathering of this data, four to six satellites signals were available.

Results. Table 2 is a cumulative probability distribution for the acquisition time of three or more satellites. It is expected that the satellite acquisition and navigational solution time will lengthen as the off time increases. This will be due mainly to the increasing uncertainty of the local oscillator. For the receiver tested, the SEL receiver, this effect was not observed out to the off times of eight minutes as shown by Table 2. The acquisition times for four or more satellites and the navigational solution times displayed similar characteristics. Since there was no significant difference in the data based on the off times, the data was analyzed as a single group as opposed to being grouped and analyzed based on the off times.

For each of the simulated surfacings the receiver was turned on for the specified on time with the computer recording the Nav String message. The Nav String message was then examined for the time it took the receiver to acquire three or more satellites, four or more satellites, and a valid navigational solution.

TABLE 2: Cumulative Probability Distribution for the Time to Acquire Three or More Satellites in Seconds

% Acquisition	0.5 min Off Time	1 min Off Time	2 min Off Time	4 min Off Time	8 min Off Time
50	3	2	4	4	2
80	10	2	8	7	12
90	13	3	12	14	22
100	27	5	20	17	23

Table 3 represents probability distributions, at the listed percentages, for satellite acquisition and navigational solution times. Every simulated surfacing acquired three or more satellites. However, 16 of the 150 simulated surfacings did not acquire four or more satellites and 64 of the 150 simulated surfacings failed to provide a navigational solution in the 30 second on time.

To determine the accuracy of the real time solutions, the GPS antenna was placed above an accurately surveyed site, so that its true latitude and longitude were precisely known. These were compared to the latitudes and longitudes provided by the GPS receiver and then the errors in latitude and longitude were generated. Figure 1 is a plot of these errors. As Figure 1 shows the greatest horizontal error was about 115 meters. The 50th percentile for the horizontal errors is 30 meters, and the 90th percentile is 80 meters. Table 4 shows the average, median, and standard deviation of the latitude errors, longitude errors, and horizontal or position errors.

TABLE 3: Cumulative Probability Distribution for the Time to Acquire Three or More Satellites, Four or More Satellites, and Navigation Solution in Seconds

% Acquisition	3 or More Satellites	4 or More Satellites	Navigation Solution
50	2	5	26
60	2	7	> 30
70	3	10	> 30
80	4	13	> 30
90	9	> 30	> 30
100	27	> 30	> 30

At this point an initial conclusion can be drawn about the use of this GPS receiver for AUV navigation. So far, it appears to meet the minimum required objectives for the acquisition of three or more satellites in 30 seconds or less as well as providing a navigation solution in 30 seconds or less 57% of the time. Perhaps more encouraging is that this engine does indicate that off the self GPS engines may be suitable for employment in AUV applications.

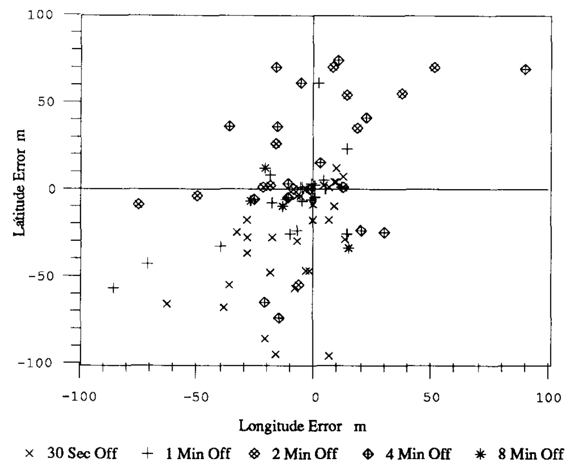

Figure 1: Latitude and Longitude Error Distribution in Meters

Although the SEL receiver was tested under an unusual operational condition, i.e., intermittent power supply to the receiver, the test results show that the accuracy of the real-time positional solutions confirmed the DoD policy, an accuracy of 100 meters in real time while S/A is on.

TABLE 4: Average, Median, and Standard Deviation for Position Errors

	Latitude Error	Longitude Error	Horizontal Error
Average	-7	-7	36
Median	-4	-5	28
Standard Deviation	37	25	29

The SEL receiver designed for civilian use does not have an ability to decode the correction for S/A; nevertheless, the accuracy from our test is very good for real time navigation compared with those available through any alternative open ocean positional devices.

AUV Mission Employment with GPS Aided Navigation

There are many ways in which GPS may be used for and incorporated into AUV navigation. Two methods, however, represent typical ways to incorporate GPS into AUV navigation. These methods involve transits and high precision or detailed work.

In many employment applications for AUVs, a transit of some distance may be required to reach or return from the mission area. In addition, a simple transit of some distance of itself may be the mission. GPS provides an outstanding navigation method for these transits. Using real time GPS navigational solutions, a mission computer or navigation system would be able to determine the course and speed required of the AUV to reach the next waypoint or destination. Depending on the transit depth of the AUV, these navigational solutions could be continually available, provided that an antenna is constantly exposed. Periodic navigational solutions, or solutions upon event such as changing course to avoid an obstacle, as determined by the mission computer, could also be provided. In this case, a compass or inertial system could be used to control heading to the next desired waypoint while the AUV is submerged. The accuracy and proven performance of GPS would ensure a very accurate launch and forget transit (from a navigational perspective) of an AUV.

One of the primary functions of AUVs, in general, is to locate objects of interest under water. In order to successfully employ an AUV to accurately locate objects of interest it must be submerged. This, however, does not preclude the use of GPS in this type of high precision or detailed work. If the area of operation is shallow water 50 to100 meters of depth, two methods may be employed when an object of interest is found.

One method involves continued submerged operation. Before the AUV submerges a GPS fix is recorded and an INS or other dead reckoning system is initialized. When the AUV submerges, it continually records navigation data. If objects of interest are found the AUV records the time of such events. Upon return, the GPS fix taken before the AUV submerged is differentially processed, and this data is fused with the navigational information to accurately determine the locations of objects of interest. The key feature is that the internal navigational system allows for continued submerged operation. How long the AUV will be able to stay submerged without a GPS fix depends on the drift rate of this inertial system. However, submerged times of five minutes or longer seem to be possible with new low cost, low power, small size INS systems now entering the market [12].

Another method to compute the difference in position from a submerged object and a surface location of a GPS fix is to use a pop up maneuver that uses only inexpensive sensors. Depth change can be accurately measured with simple sensors. In addition, if the climb and orientation are measured to a degree or so, the true location can be determined. An inexpensive gyro could sense the climb angle and a compass the orientation.

On a differential basis, the horizontal movement, ΔH, is just the depth change, ΔZ, times the cotangent of the elevation angle, θ,

$$\Delta H = \Delta Z \cot\theta \qquad (1)$$

This can be decomposed into north and east components with the compass heading. This process can be integrated in small steps reducing the effect of random measurement noise. Systematic noise could be calibrated pre-mission. The horizontal error is proportional to the cosecant squared of the average rise angle; that is,

$$\frac{dH}{d\theta} = -Z\csc^2\theta \qquad (2)$$

From this relation, if the AUV rises 100 meters at an average angle of 10 degrees, and the angle sensors all have residual systematic errors of 0.5 degrees, the horizontal position error would be about 30 meters. For an ascent angle of 45 degrees, the same conditions lead to a 2 meter error. Errors in shallow ascents could be reduced by following a spiral path. This method does not, however, account for lateral translations of the vehicle due to currents or sideslip.

Future Work

This paper presents only the initial phase of ongoing work at the Naval Postgraduate School for incorporating GPS into AUV navigation. Two designs for a GPS system have been developed. The first system, (the interim design) makes use of the pop-up tactic previously mentioned. The main advantage to this approach is that by using a low cost vertical gyro instead of a full INS system, a less expensive system can be developed and tested. The second design (the baseline design) incorporates a strap down INS system allowing for longer submerged times. The baseline design is presented in Figure 2.

Preliminary investigation of the operational characteristics of the different components and their power requirements have proved to be very promising [12,13]. With the advent of VLSI and other advanced technologies it is possible to build a low cost, low power, small size GPS navigational package that would directly interface with the AUV mission computer. The Naval Postgraduate School intends, at this time, to build a breadboard system, based on the interim design, for detailed error analysis. Eventually, such a GPS/INS package system will be incorporated into the NPS Model II AUV for evaluation. Some details of the current characteristics and capabilities of this vehicle can be found in [14].

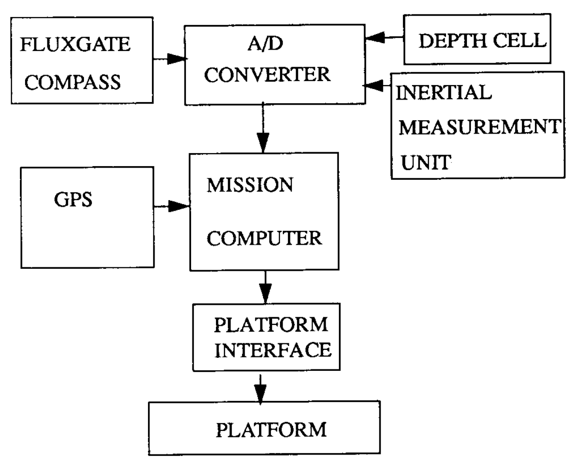

Figure 2: Baseline Design for GPS/INS Navigation and Mission Control being Developed by Naval Postgraduate School

Conclusions

GPS is the most accurate open ocean positioning system currently available. With the advent of low cost, low power, small size single board GPS receivers, it may be very useful to incorporate GPS into AUV navigation. GPS could be used as a primary navigation system or as a supporting one depending on the AUV mission employment. The requirement to expose a GPS antenna clear and free of the water is the primary drawback to incorporating GPS into AUV navigation. However, that does not preclude the use of GPS for navigating AUVs, especially in transits or shallow water high precision work. The use of GPS could be integrated with the use of any other navigational system.

The experimental tests conducted on the SEL receiver were designed to initially determine the suitability of GPS for AUV employment. These results meet our minimum criteria of AUV employment as established in this paper. However, what is more important than specific conclusions about the SEL receiver, is that it was demonstrated that small, low cost, low power GPS receivers, in general, are suitable for AUV applications.

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