Development of an Autonomous Underwater Vehicle for Sub-Ice Environmental Monitoring in Prudhoe Bay, Alaska

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ABSTRACT

The investigation of environmental impacts from oil development in the Prudhoe Bay region of the Beaufort Sea, along Alaska's northern coast is currently underway at the Florida Institute of Technology (Florida Tech). Of particular interest are the impacts of the construction of offshore gravel islands used for oil drilling and production. Construction of these islands may contribute to an increase in suspended sediment concentrations in the waters of Prudhoe Bay, which could have adverse affects on the health of local marine ecosystems.

In response to the needs of the project, the Underwater Technologies Laboratory (UTL) at Florida Tech has developed a unique Autonomous Underwater Vehicle (AUV). The purpose of this AUV is to perform automated point-to-point data collection missions underneath the thick winter ice sheet.

This paper presents the overall design concept of the AUV, along with the design of the prototype vehicle's various subsystems including propulsion, navigation, environmental sensor payload, CPU, power, and software.

INTRODUCTION

In the Prudhoe Bay region of the Alaskan Beaufort Sea, oil drilling and exploration efforts are underway and expanding. Currently, the Mineral Management Service (MMS), under the Department of the Interior (DOI), has been tasked with the responsibility of studying the effects of offshore gravel-island based oil development on the marine environment. As part of this initiative, The departments of Oceanography and Ocean Engineering at Florida Tech, under the Division of Marine & Environmental Systems (DMES), were contracted to participate in a large research effort in this region, known as the *Arctic Nearshore Impact Monitoring in the Development Area* (ANIMIDA) Project [11].

As a part of this research effort, studies are being conducted on the currently-operational Northstar Island, as well as another site slated for gravel-island construction, known as the Liberty Prospect (see Fig. 1).

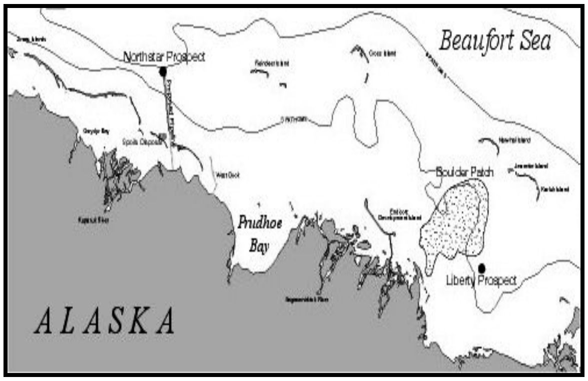

Fig. 1: Map of the ANIMIDA Study Area

A primary interest in this region is the increase in suspended sediment concentrations in Prudhoe Bay due to gravel-island construction and erosion. Such increases may have deleterious effects on marine plant life, due to decreased light transmission through the water column. In order to study this problem, researchers in the Chemical Oceanography group, under Dr. John H. Trefry, collect conductivity, temperature, depth, (CTD) and turbidity data using various field instruments, and conduct trace metal and hydrocarbon analyses on the waters and soils in and around Prudhoe Bay [10].

During the summer months, instruments are deployed directly from small boats. However, to collect winter data, holes must be drilled in the ice, in order to perform sensor casts. This activity is shown in Figure 2.

This method of data collection is highly inefficient and time consuming. Furthermore, it offers poor spatial resolution, confining data collection to a few discreet points over the entire field of study. To automate and improve this process, the Ocean Engineering group was enlisted to design, develop and construct an Autonomous Underwater Vehicle (AUV) for use in under-ice data collection in the Prudhoe Bay area.

Fig. 2: "Drilling for data" in Prudhoe Bay, near Northstar Island

Table 1 lists some basic design criteria used to create the 1st generation prototype "Prudhoe Class" AUV, known as "Tuvaaq".

Table 1: AUV Prototype Design Criteria

Autonomous Data Collection Parameters	C,T,D, Turbidity
Autonomous Sub-Ice Navigation	Yes
Autonomous Depth Following	Yes
Minimum Operating Temperature (in water)	-1.8 °C
Minimum Storage Temperature (in air)	-20 °C
Maximum Water Current	0.05 m/s
Maximum Operating Depth	50 m
Maximum Speed	1 m/s
Maximum Entry/Exit Hole Dia.	0.6 m
Maximum Ice Thickness at Hole	2 m
Maximum Distance Between Entry/Exit Holes	500 m
Maximum Number of Persons required to deploy Vehicle	2 persons

PROTOTYPE AUV DEVELOPMENT

Early on, it was realized that the most difficult problems to overcome in the development of this AUV would be navigation, control, and launch & recovery.

The navigational problem presents itself in several forms. First, the use of Differential GPS is unavailable due to the fact that the vehicle is operating both underwater and under ice, preventing even periodic surfacing for GPS position fixes.

Second, inertial navigation systems (INS) progressively accumulate error due to approximations in integration and limitations in sensor resolution. Only with periodic absolute position fixes (i.e. GPS or Acoustic) and fast Kalman Filtering to bound the accumulated error, could this be achieved [4]. Due to the restricted budget and timeframe for the project an INS is not included in the present configuration.

These design restrictions necessitated the development of a more accurate, yet simple, acoustic homing system. This system allows the vehicle to navigate with respect to a fixed acoustic beacon, located at the vehicle's intended exit hole.

With the navigational problem addressed, the control, launch, and recovery issues were examined since they are directly tied together. Typically, modern AUVs are designed with a torpedo-shaped form that provides the advantages of low hydrodynamic drag, ease of maneuverability over long distances, and low power consumption. While this basic design offers some payoffs in open water survey and data collection missions, it lacks the precise positioning and station keeping abilities of a multi-thruster remotely operated vehicle (ROV) design. Due to the nature of the deployment environment for this project, it was determined that such maneuvering and control characteristics were of utmost importance, since the vehicle must be able to be launched and recovered through a 2ft diameter hole, through a 6ft thick sheet of ice, and may have to navigate around random, closely-spaced ice-spikes. These aspects require the ability to precisely position the vehicle at low speeds underneath the exit hole.

Such fine control and station-keeping tasks are difficult for a conventional torpedo-shaped vehicle, steered by control surfaces as the turning radii for such systems are usually very large and a constant forward motion is required in order to generate lift on the control surfaces. Since the positioning tolerance for recovery of the AUV is so tight, failing to "catch" a torpedo-shaped vehicle during its first pass to exit would mean a complete wide turn-around in a decreasing spiral path, rather than a simple small position correction. Additionally, the horizontal flight characteristics of a torpedo-shaped vehicle further complicate the recovery effort, as the vehicle must be turned vertical before it can be lifted from the exit hole.

It was also determined that the benefits of a torpedo shaped AUV's low hydrodynamic drag were of little consequence since this particular AUV would be moving at low speeds (< 1 m/s).

The result of these design restrictions lead to a rather unconventional cylindrical vehicle shape, shown below in Figure 3.

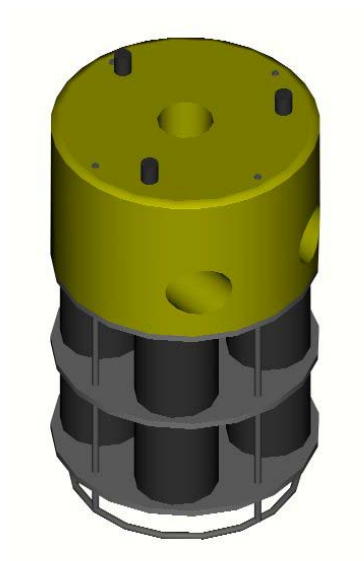

Fig. 3: Prudhoe Class AUV Concept

The Prudhoe Class AUV mission concept can be outlined as follows (a visual representation of this plan is shown in Fig. 4):

1) Drill a single 2ft diameter entry hole and one or more exit holes in the ice sheet at the data collection site.

2) Deploy a simple acoustic beacon in the desired exit hole, approximately 1ft below the bottom of the ice (7ft water depth).

3) Deploy the AUV into the entry hole using a simple hand-operated rope winch. The mission is in a standby mode, and begins when the vehicle senses 1ft of water depth.

4) The AUV executes its mission by homing-in on the beacon and navigating simple paths with respect to the beacon, a digital compass, and depth sensor. Data from the on-board CTD & Turbidity sensors is logged along the way.

5) Once at the exit hole, the vehicle ascends, positioning itself to remain underneath the hole.

6) The vehicle is retrieved with the use of a simple hook and rope and concludes its mission once it senses less than 1" of water depth (i.e. it has been extracted from the water).

7) These point-to point missions can be repeated as necessary to map the whole field of interest.

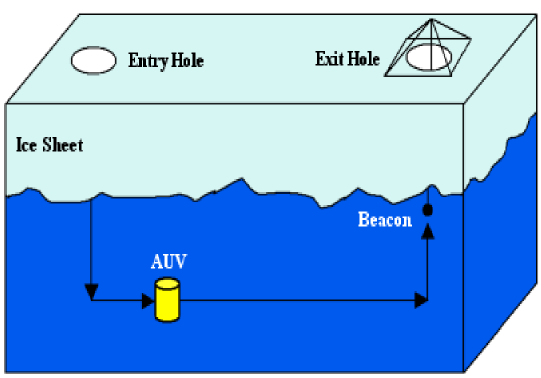

Fig. 4: Basic AUV mission plan

MODELING & SIMULATION

Upon completing the preliminary design, a MATLAB® Simulink simulation was created to model plant dynamics, refine controller designs, and examine the feasibility of the overall design through execution of test missions. This simulation was later used to develop the prototype and its control software.

VEHICLE DYNAMICS

The dynamics of the AUV were derived with respect to a body-fixed coordinate reference frame (Fig. 5) possessing the following six degrees-of freedom (DOFs) and their respective derivatives:

x (surge) – linear motion with respect to the longitudinal axis
y (sway) – linear motion with respect to the transverse axis
z (heave) – linear motion with respect to the vertical axis
ϕ (roll) – rotational motion about the X-axis
θ (pitch) – rotational motion about the Y-axis
ψ (yaw) – rotational motion about the Z-axis

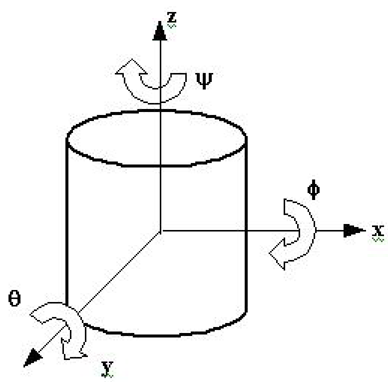

Fig. 5: Body-Fixed Coordinate Ref. Frame

Inputs to the system are defined as follows:

T_1 – Thrust force from the port thruster
T_2 – Thrust force from the starboard thruster
T_3 – Thrust force from the vertical thruster
$F_{ext(x,y,z,\psi)}$ – External disturbance forces (water currents, etc)
$F_{d\ (x,y,z)}$ – linear hydrodynamic drag forces due to vehicle motion, defined by the equation:

$$F_d = C_d * \rho * A_p * \frac{V_0^{\ 2}}{2}$$

where:

C_d = coefficient of drag
ρ = density of seawater
A_p = projected drag area
V_0 = velocity of drag surface
(Note: rotational skin friction is considered nominal)

Other relevant parameters:

m – vehicle mass (approx. 200lbs = 6.2 slugs)
D – separation between horizontal thrusters T_1 & T_2 (11" = 0.91667ft.)
W_{auv} – weight of the vehicle in water (assume neutral buoyancy, = 0)
I_z – moment of inertia about the (vertical) z-axis (6.009 slug·in^4)

Before developing the equations of motion, it should be noted that y, ϕ, & θ are all uncontrollable DOFs, based on our thruster configuration. Furthermore, ϕ, & θ can be eliminated due to passive stabilization with keel weights. Therefore, we need only be concerned with the 4 DOFs required to position the vehicle in space: x, y, z, ψ, three of which are controllable: x, z, ψ.

As shown in [5], the dynamic equations of motion can be derived in the following manner:

Taking the sum of forces in the X, Y, and Z-directions, and solving for acceleration yields:

$$\ddot{x} = \frac{(T_1 + T_2) + F_{dx} + F_{x\,ext}}{m} + \dot{y}\dot{\psi}$$

$$\ddot{y} = \frac{F_{dy} + F_{y\,ext}}{m} + \dot{x}\dot{\psi}$$

$$\ddot{z} = \frac{T_3 + F_{dz} - W_{auv} + F_{z\,ext}}{m}$$

where:

$F_{d(x,y,z)}$ was previously defined.
$F_{xext} = F_{yext} = F_{zext} = 0$ (assume no external currents or disturbances)

Taking the sum of moments about the Z-axis yields:

$$\ddot{\psi} = \frac{(T_2 - T_1)\left(\frac{D}{2}\right) + M_{z\,ext}}{I_z}$$

where:

$M_{z\ ext} = 0$ (assume no external disturbances about the Z-axis)

For the purposes of the simulation, these equations of motion yield eight state variables and three independently controllable system inputs:

$$X=\begin{bmatrix}x_1\\x_2\\x_3\\x_4\\x_5\\x_6\\x_7\\x_8\end{bmatrix}=\begin{bmatrix}x\\y\\z\\\psi\\\dot{x}\\\dot{y}\\\dot{z}\\\dot{\psi}\end{bmatrix}$$

$$u=\begin{bmatrix}F_x\\M_z\\F_z\end{bmatrix}=\begin{bmatrix}T_1+T_2\\(T_2-T_1)\left(\frac{D}{2}\right)\\T_3\end{bmatrix}$$

where u is a function of T_1, T_2, and T_3, the inputs to the plant model from the three thruster controllers.

MISSION PLANNER

The mission planner is the high-level decision maker on-board the AUV. It monitors all system states and issues commands to the low-level thruster controllers. The mission planner observes the states in X_{nav}, as well as flags from emergency events, such as collision avoidance system commands and leak detection. Mainly, the mission planner decides how fast to go, what depth to descend to, what heading to follow, etc. During simulation trials, the mission planner was set to command the vehicle to go directly to the beacon ($\alpha = 0$), dive to two different depths depending on the range to the beacon, and when close to the beacon, surface and slow down. The mission planner also issues a flag, which stops the simulation when the vehicle is within 1ft of the beacon, and at 1ft. depth (below the ice), which is assumed to be within sufficient capture range of the exit hole.

LOW-LEVEL CONTROLLERS

The low-level controller set consists of three controllers, depth, speed and heading, and a series of mixing functions to generate resultant thruster outputs.

The simplest of the three, the depth controller, is implemented as a conventional PID controller with negative unity feedback.

Heading correction is achieved by a sliding-mode controller [8], with a +/- 3 degree boundary layer to reduce chatter.

A Closed-loop forward speed control is difficult to accurately achieve, since the vehicle's ground speed is not being directly measured. Thus, speed control is performed in an open-loop fashion, as simply a percent total thrust command from the mission planner for different beacon ranges.

MECHANICAL LAYOUT

As stated previously, the mechanical design of the Tuvaaq AUV is based on research into ROVs used in tight-quarter working environments. The basic layout of the vehicle is shown in Fig. 6, and consists of four vertically-mounted pressure vessels (two for electronics, two for batteries), two parallel horizontal thrusters, one vertical thruster, an externally mounted CTD, turbidity sensor, and acoustic transducers, and upper & lower protection cages.

This design allows the vehicle to fit vertically into a 2ft. diameter hole, simplifying launch and recovery through the thick ice on the Beaufort Sea. Also, the use and placement of the thrusters simplifies control by decoupling vehicle motions in the vertical and horizontal planes and allowing small position corrections at low speed. This low speed positioning, plus the advantage of being able to make a complete 360° turn within its own body diameter, makes the vehicle extremely maneuverable in tight quarters and gives it station-keeping ability.

Fig. 6: Assembled AUV

Each pressure vessel consists of a 15”-long, 6” diameter 6061-T6 aluminum pipe with a welded flat endplate (Figure 7). This sizing was chosen to accommodate the PC/104 electronics stacks and batteries discussed in later sections, with ample room for future electronics add-ons.

Fig. 7: AUV pressure vessel (1 of 4)

The pressure vessels are held in place by PVC spacer plates (Fig. 8). The thruster assembly consists of three thrusters mounted into a syntactic foam buoyancy module (Fig. 6, yellow). The vehicle is held together by threaded-rods that compress the housings, thruster/buoyancy module, acoustic transducer array, environmental sensors, and protection cages together into a single unit.

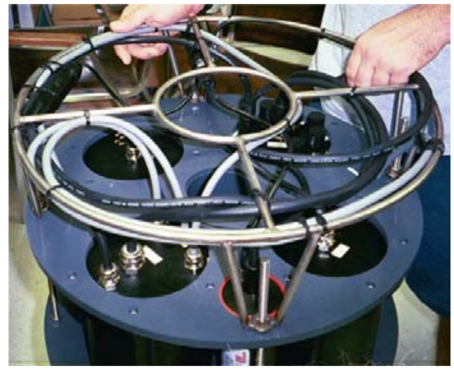

Fig. 8: Underside of AUV, with spacer plate and skid cage shown

PROPULSION

The propulsion system is composed of three brushless 12VDC electric thrusters with water-lubricated bearings. The thruster assemblies and accompanying controller cards have all been custom designed at the Florida Tech UTL.

NAVIGATION

The Tuvaaq vehicle is outfitted with two basic navigation systems: a dead reckoning system and an acoustic homing system. The dead reckoning system consists of an electronically gimbaled digital compass, roll/ pitch sensor, a depth sensor, and hall-effect tachometers on each thruster motor. Of course, this system is highly error-prone, especially in the Arctic, where close proximity to the North Pole can cause magnetic compasses to give erroneous readings. However, it is useful for basic open water field-testing of the AUV.

The acoustic homing system is based on the Super-Short-Baseline method, or SSBL. The theory behind this technique is as follows. Sound in water propagates as a pressure wave, oriented orthogonally to its direction of motion. As the pressure waves meet a line of transducers oriented at an angle to their direction of travel, the incoming waves arrive at each transducer at different times. These time differences can be used to trigonometrically calculate the bearing angle to the acoustic source. Furthermore, since it is necessary to discern which direction the acoustic signal is coming from in the full 360-degree horizontal and vertical planes, a single-line array would be unsuitable. Therefore, a transducer triplet array was designed, so as to allow this determination (see Fig. 8 and [2]).

As shown in Figure 8, the angle α gives the horizontal bearing to the beacon and the angle β gives the vertical bearing. These angles are calculated in the following manner:

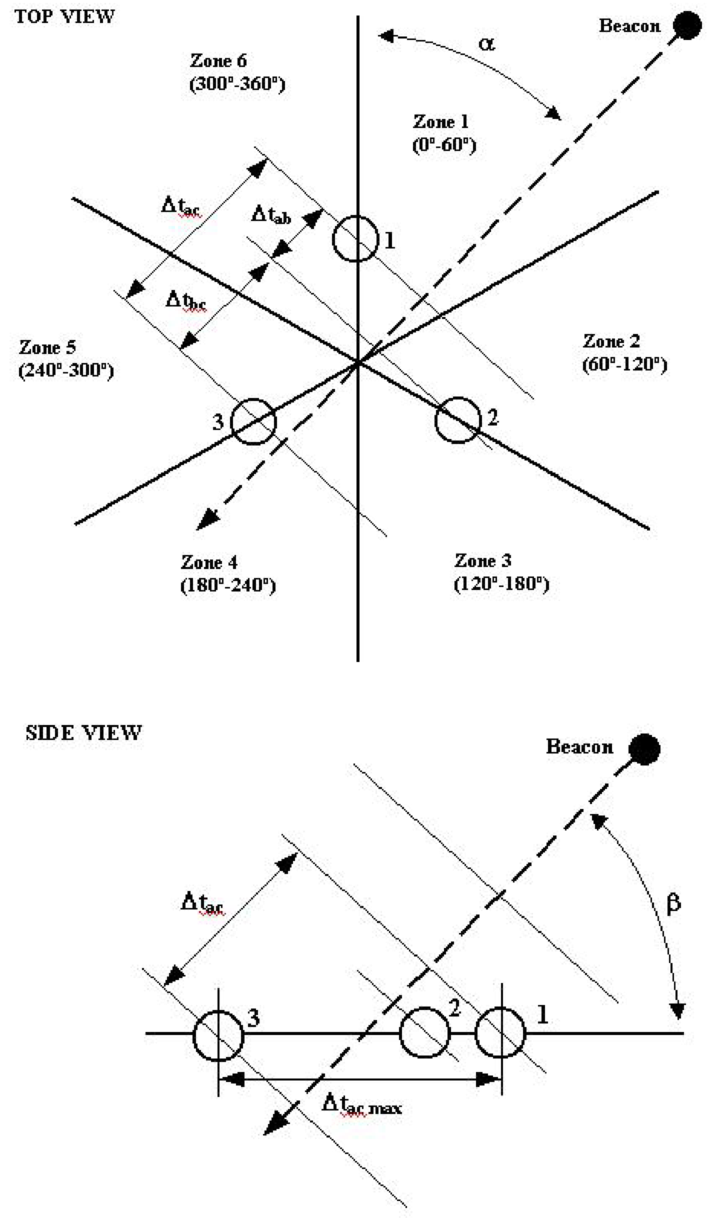

Fig. 8: Propagation of hydroacoustic waves across a triangular SSBL transducer array.

1. Logically resolve which 60º zone the beacon is in based on the order in which the transducers detected the signal.

2. Determine the horizontal bearing angle (α) within the appropriate zone through time-of-arrival ratios:

$$\alpha = \left(\frac{\Delta t_{bc}}{\Delta t_{ac}} \right) 60^{o} + X$$

for odd-numbered zones (1,3,5)

$$\alpha = \left(\frac{\Delta t_{ab}}{\Delta t_{ac}} \right) 60^{o} + X$$

for even-numbered zones (2,4,6) where,

Δt_{ab} = time difference between the first and second transducers to detect the signal.
Δt_{bc} = time difference between the second and last transducers to detect the signal.
Δt_{ac} = time difference between the first and last transducers to detect the signal.
X = lower angle limit of each zone (e.g. for Zone 5, X = 240)

3. Determine the vertical bearing angle (β).

$$\beta = Cos^{-1}\left(\frac{\Delta t_{ac}}{\Delta t_{ac\max}} \right)$$

where,

Δt_{ac} = time difference between the first and last transducers to detect the signal.
$\Delta t_{ac\,max}$ = Maximum time difference between the first and last transducers to detect the signal, based on the flat-line distance between them and an approximate speed of sound, C_s = 1500 m/s = 59055.118 in/s.

The horizontal bearing angle (α) functions like an acoustic compass heading, guiding the vehicle towards the beacon. Note that knowing the speed of sound is not necessary when calculating α, because it is based on *relative* time differences between the transducers. This allows high accuracy in determining this angle, despite changes in the speed of sound between the beacon and the vehicle.

The vertical bearing angle (β) is useful for two reasons. If the vehicle depth and beacon depth are known, the two can be subtracted, giving a vertical offset (Δd). This vertical offset and the vertical bearing angle can then be used to triangulate the position of the beacon, thereby allowing approximate determination of horizontal range (R), as shown below.

$$R = \frac{\Delta d}{Tan\beta}$$

Secondly, as the vehicle approaches the beacon from below, β approaches zero, allowing the vehicle to determine when it is directly under the beacon. The vehicle can then make a simple vertical ascent to the exit hole. In fact this is the most important feature of knowing β. Since the microcontroller assumes a constant for the speed of sound (1500 m/s), precise determination of R is difficult. However, by monitoring this angle as it approaches 90º, the mission planner knows that it is moving towards the beacon. Thus, the mission planner can find the beacon by driving β towards 90º, and begin making its ascent when β is sufficiently steep.

Fig. 9 shows the SSBL receiver array mounted on a test fixture. It's accompanying amplifier / signal-processing card was also designed at the Florida Tech UTL. This card encompasses amplification, filtering, and ping detection circuitry, as well as a microcontroller which performs the necessary trigonometric calculations and outputs α & β over a standard RS-232 connection. Its counterpart is a low-cost 37KHz pinger, outputting 163dB pings at 2Hz.

Fig. 9: SSBL Receiver Array

ENVIRONMENTAL SENSOR PAYLOAD

As the purpose of the Tuvaaq AUV is to monitor environmental data, selection of the sensor payload is critical. Ultimately, the vehicle is nothing more than an autonomous platform, and can be adapted for other data collection missions simply by changing the sensor payload. The Smart CTD sensor package, manufactured by Applied Microsystems, Ltd., was selected with an add-on Infrared Light-Scattering Turbidity Sensor (LSS) from WetLabs, Inc. The depth reading from the CTD is also fed to the PID depth controller on board the vehicle as a feedback term to navigate the vehicle the in the water column.

The CTD sensor is mounted on the side of the vehicle, and the LSS is attached to the underside of the vehicle such that it has a clear visual path into the water column.

POWER

Ultimately, the ability of an AUV to perform its mission is dependent on its power supply. For this vehicle, the power system consists of four 12V, 12 AH Sealed-Lead-Acid (SLA) batteries, held in two housings, and a PC/104 power supply board.

Although not the highest power-density battery available, lead-acid batteries are simple, widely used, and very low-cost. Despite large power losses in cold weather, it is estimated that the power cells will offer 8-10 30 minute missions before recharging is necessary.

COMPUTER STACK

The Central Processing Unit (CPU) Housing is the "brain" of the vehicle; running all control, mission planning, and data-logging software. This "command center" ties all of the vehicle subsystems together. For the Tuvaaq vehicle, a PC/104+ form factor was chosen. The main PC/104 stack consists of a Pentium-based single-board computer (SBC), serial port expansion card, 802.11 wireless Ethernet card, power supply, and hard drive.

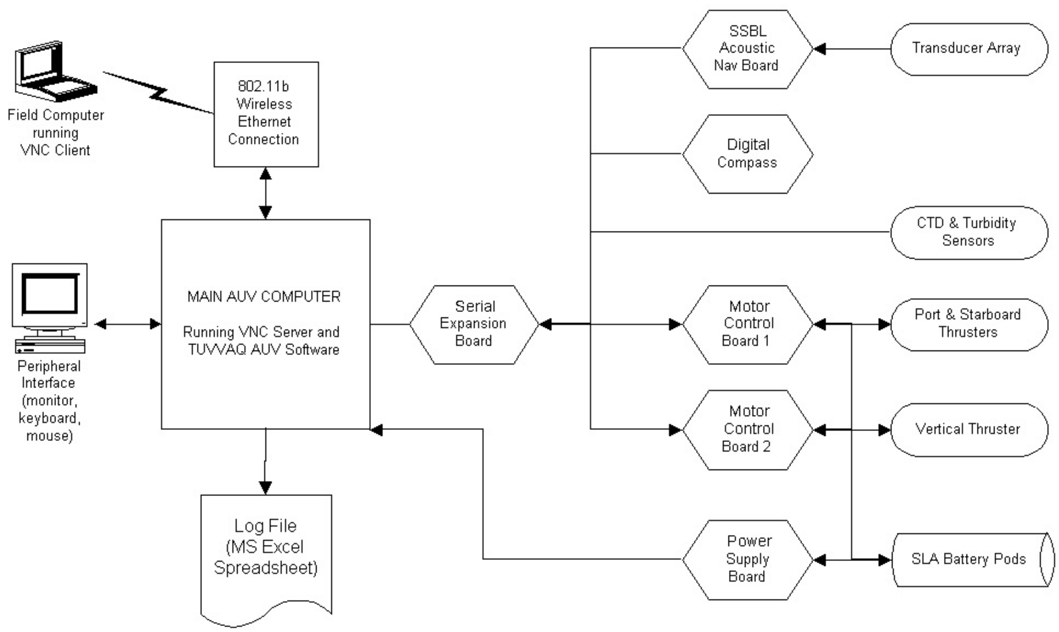

Fig. 10: Tuvaaq High-Level System Architecture

Figure 10 shows a high-level diagram of how all of the vehicle subsystems are tied together through the CPU.

INTERNAL COMMUNICATIONS

Internal communications with sensors, navigation systems, motor drivers, etc., is achieved through an RS-232 serial network with 10 standard RS-232 serial ports (also configurable as RS-485 or RS-422). The advantage of this system includes the ability to add additional serial expansion cards to the PC/104 stack, and ease of interfacing with PIC Microcontrollers (as in the case of the Brushless DC Thruster Controller Boards and SSBL Acoustic Navigation Board). With the use of only standard ASCII text strings for data transfer, the software and hardware development is simplified, and adds to the overall robustness of the system. Furthermore, commercial devices such as the on-board compass and CTD, readily offer RS-232 communications, simplifying future instrument additions.

EXTERNAL COMMUNICATIONS

In order to set mission parameters, execute on-board software, and download data, a means of external communication with the AUV is necessary. When the PC/104 stack is exposed, the CPU has the ability to directly connect to a standard keyboard, monitor, and mouse, as well as floppy and CD-ROM drives. This is the simplest means of communication for making major changes and debugging problems.

However, when the stack is sealed in the CPU housing, access is limited. In harsh environments such as Alaska's North Slope it is necessary to eliminate the need for hard-wire communications and multi-pin waterproof bulkhead connectors. Consequently, a low-cost 802.11b Wireless Ethernet (WLAN) card was selected for communications between the AUV and a field laptop with another WLAN card installed. Communication is achieved via an open-source remote desktop program, known as VNC.

CONTROL SOFTWARE

Ultimately, all datalogging, navigation, motor control, and mission planning functions take place on the main CPU. In the case of the Tuvaaq AUV, the Microsoft Windows 2000® Operating System was chosen for ease of use, availability, and rapid prototype development. In the future, the AUV's software may be ported to a Real-Time Operating System, for increased robustness and real-time compliance.

The high-level AUV software program, known as simply "TUVAAQ" (Fig. 11), was written in National Instruments' LabVIEW®. This single, multithreaded application provides all necessary data acquisition, control, logging, and user interface features necessary to run the AUV. The use of LabVIEW® was also chosen for its rapid prototyping capability, ease of use, and powerful hardware integration features.

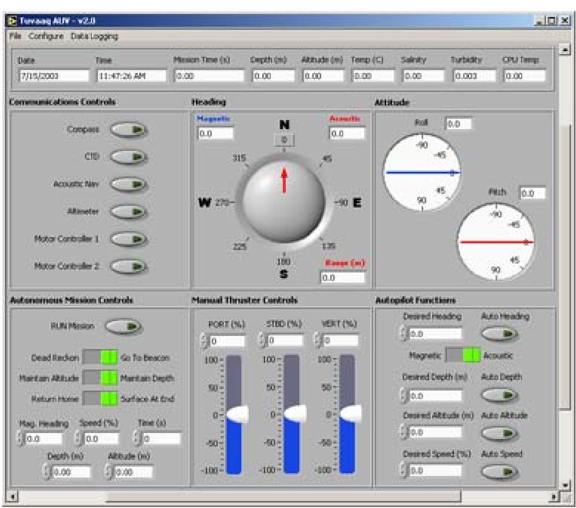

Fig. 11: TUVAAQ AUV Control Software (Main GUI)

CONCLUSION

This paper has described the design and construction of an Autonomous Underwater Vehicle (AUV) for use in under-ice data collection in Prudhoe Bay, Alaska.

In conclusion the Tuvaaq AUV shows genuine promise as a viable under-ice data collection system. The design of the Tuvaaq vehicle allows for the electronics, software, and pressure vessel technologies to be used in other vehicle shapes, thereby extending its applications to open-water and higher-speeds. The Tuvaaq is a new type of AUV for use in the Arctic, and is also a base technology that will be used in future AUV development in the Underwater Technologies Laboratory at Florida Tech. Additionally, the design of an acoustic collision avoidance system for use on the Tuvaaq vehicle is also underway at the UTL.

The Tuvaaq AUV is currently undergoing pool tests at Florida Tech and will begin sea trials during the fall of 2003. Under ice missions will be performed during the winter of 2004 in New Hampshire. The vehicle will then be deployed on its real mission in Northern Alaska during March of the following year.

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