ABSTRACT

The Autonomous Benthic Explorer (ABE) is a vehicle that will perform scientific survey of the seafloor over an extended period of time without a support vessel. The vehicle has been designed to complement the existing manned submersible and remotely operated vehicle systems available to the scientific community. A primary application of ABE will be repeated surveys of hydrothermal vent areas at depths of 4000 meters. Specifically, ABE will be able to provide data concerning the long term variability of hydrothermal vents, a task that existing assets cannot accomplish. This paper discusses the motivation for ABE, outlines the specifications and basic design approach, and describes critical technical problems. Initial and future ABE mission scenarios are also discussed.

INTRODUCTION

The Autonomous Benthic Explorer (ABE) is an underwater vehicle designed for seafloor scientific survey. The capabilities of ABE have been carefully chosen to complement and extend current deep-ocean scientific assets such as manned submersibles, remotely operated vehicles, and fixed instruments. ABE is not intended to duplicate existing capabilities in an autonomous mode, but rather to perform tasks that cannot be done otherwise.

ABE is primarily designed for research on hydrothermal vents, dynamic structures which occur in seafloor spreading regions along the Mid-Ocean Ridge [1] where the proximity of the underlying magma drives an associated hydrothermal circulation. While hydrothermal vents are better understood than they were a decade ago, better observations are required to answer many basic questions. For example, the chemical flux from the vents may dominate and stabilize the global long-term composition of seawater or it may be trivial, depending on whether the high or low value of the best available estimate of total flux is used [1]. We know very little about the temporal variability of the vents: magma may be delivered to the surface steadily or in batches. It appears that there are both steady emissions and periodic releases of large amounts of water (called mega-plumes).

Although ABE is an ambitious project, it is important to realize that it is largely a conservative design based on proven technology. Hitherto, most AUVs have been designed to demonstrate some capability. ABE, however, must work for a living. Its initial concept is therefore as straightforward as possible.

Several considerations dominate the ABE design. ABE must function unattended for prolonged periods of time. Initial deployments will probably last less than 6 weeks, but the design will accommodate mission lengths of up to a year. It must function at depths of up to 6000 meters. While ABE doesn’t have to rival ROV’s or manned submersibles in terms of the number of sensors or
the volume of data, it must make adequate observations to meet basic survey standards. In the pre-
liminary ABE scenario, the operational site will be prepared with acoustic beacons and an anchor-
ing point by submersible or ROV.

In its initial phase, ABE will be acoustically navigated, carry optical imaging sensors, and will be
able to measure the basic physical properties of seawater. This sensor suite will permit precisely
navigated photo surveys to be repeated. A preliminary design of ABE is shown in figure 1.

![Diagram of ABE](image)

**Figure 1.** This diagram summarizes the basic ABE design. The vehicle utilizes glass spheres for
floatation, and the basic shape will permit efficient transit as well as good hover control. The vehi-
cle will be a very stable sensor platform.

**TYPICAL MISSION SCENARIO**

A typical ABE deployment will utilize four modes: descent to the site, resting in low power mode,
survey, and ascent for retrieval. These modes are summarized in figure 2.

The descent mode will be conducted in two phases. In the first phase, ABE will utilize a drop-
weight system for an energy efficient free-fall to the seafloor. The well faired body of ABE will
provide sufficient lift to permit a 3:1 glide angle to provide considerable horizontal travel and to
deal with currents in the water column. During descent, the vehicle will home on a low frequency
(30 kHz) beacon deployed during site preparation. When sufficiently close to the bottom, the sec-
ond descent phase will begin. ABE will drop the descent weight, becoming nearly neutrally buoy-
ant and make fine buoyancy adjustments to minimize vertical drift. It will then actively home on
the anchor point with thrusters. ABE will mechanically latch to the prepositioned anchor point
and utilizing simple acoustic telemetry, will report its status to the surface vessel after which it can
go into a low-power sleep mode.

In the low-power sleep mode, ABE will draw only 10 milliwatts. Because it will be mechanically
latched to the anchor point, thrusters will not be needed. Most of the on-board computing ele-
ments will be shut down, with the exception of a microcomputer which remains static most of the
time but will wake up once a second to check vehicle and acoustic commanded status. This master computer will also keep track of time and will be able to power up the rest of the system, in whole or in part. For example, sensor systems may be periodically turned on to check for environmental change and the thrusters will be run occasionally to prevent fouling. When it is time to execute a survey, the master computer will bring the entire computer network, all sensors, and all actuators on-line.

In survey mode, ABE will execute precisely navigated bottom transits. The vehicle will disconnect from the anchor point and move within the work area. It will navigate with a high frequency (300 kHz) pulse-time system that can provide positional accuracy within several centimeters over a 100 meter range. For less demanding survey tasks, ABE will utilize range-bearing measurements from the 30 kHz system to transit over a larger area with less precision. Vertical position will be measured by a precision depth sensor system. The total horizontal travel distance will be between 10 and 50 km, depending on the batteries selected.

The fourth mode is the ascent to the surface. This will be done by jettisoning ascent weights either at a preprogrammed time or upon an acoustic command from the surface. The vehicle will ascend passively and will be tracked via its acoustic beacon from the recovery ship.

While ABE in its initial form will require a manned submersible or ROV for preparing the site, deployment and recovery of ABE will be possible with a much smaller, more economical ship than that required by a manned submersible or ROV. In the future, the site could be prepared by lowering (or dropping) transponders and the anchoring device from the surface.
VEHICLE DESIGN

The ABE design draws heavily on long-term experience with the manned-submersible ALVIN [2] and the ROV JASON [3]. Both are deep ocean scientific systems that have proven reliable and practical to maintain.

Vehicle Size and Shape

Low cost, long duration, good controllability, and low power consumption distinguish ABE from many other systems. The vehicle has been designed to transit efficiently at steady depth in a well controlled manner, but the vehicle must also be able to hover and maneuver along the sway and heave axes. During all maneuvers, the vehicle should act as a stable sensor platform, preferably without active pitch and roll control. The requirements for good hover control and attitude stability reduce the attractiveness of a low-drag torpedo shape.

The layout of ABE (figure 1) provides low drag, simple construction based on 17” (42 cm) glass spheres, and high static stability in roll and pitch. The design is reminiscent of the Phantom ROV [2], except that the heavy payload is slung low to improve stability. To ensure adequate scientific payload and battery capacity, a design built around 6 glass spheres was chosen. The resulting vehicle displacement will be around 450 kg. The need for low power consumption in transit requires close attention to vehicle drag. In addition to careful choice of main vehicle body and frame elements, the standard ROV design practice of using external sensors, cables, and hoses must be avoided.

Glass spheres were selected for the primary buoyancy based on their efficiency, proven reliability, and low cost. However, this choice also limits the possible shapes since the spheres are available in only a limited set of sizes.

Vehicle Dynamics

The dynamics of the current ABE design have been examined through analysis and scale model testing.

The chosen ABE design will have good stability while translating forward. An early concept, based on a circular “flying saucer” shape proved to be prone to a galloping instability under steady towing in a scaled tank test.

For the chosen design, the high separation between the center of buoyancy and center of gravity will result in very good pitch and roll stability. Model tests suggest that the vehicle will be well damped in roll, but relatively lightly damped in pitch.

ABE will generate substantial body lift when translating forward with a non-zero angle of attack. While the vehicle will be too stable to produce much pitch with the two vertical thrusters, the concept of shifting the ascent weight is being investigated to induce slow pitch changes to produce coordinated forward movement and depth changes.

The dominant hydrodynamic parameters are being investigated through tow tank tests of a 1/3 scale model. These will include the principal drag and lift coefficients. The remaining terms of importance, effective mass and inertia terms and some of the coupling terms, will be determined through full-scale system identification after the basic vehicle structure is complete.

In low-speed vehicles like ROV’s, thruster considerations have proven to dominate the dynamics [4]. Principal concerns are the placement of the thrusters on the vehicle and the dynamics of the thrusters themselves.
The preliminary placement of ABE’s thrusters represent a compromise between static efficiency, good dynamics, and fouling considerations. Two vertical and two horizontal thrusters have been positioned to produce minimal torques when thrusting vertically or to the side. Tentatively, two stern propellers have been placed at the aft end of the two main buoyancy packs to improve thruster efficiency at steady speed by wake recovery. As these thrusters will be above both the centers of mass and drag, they will create a pitching moment during acceleration and steady forward speed. This will be countered by engaging a third forward thruster placed low or by differential thrust of the vertical thrusters. The energy required to balance the pitch moment could negate the benefit obtained by placing the main forward thrusters for optimum efficiency, and final placement of the thrusters will be adjusted experimentally.

The dynamics of the thrusters is a dominant concern, particularly for fine maneuvering. Torque-controlled thrusters have been shown to have a sluggish, nonlinear response [4]. ABE’s thrusters are being designed to minimize these effects and will have responsive, well instrumented motors. Oil-filled DC brushless motors have been selected that will provide 200 watts peak and will be optimized for 100 watts. They will drive ducted propellers through approximately 15 to 1 gear reducers, which represents a good compromise between motor weight, efficiency, and windage losses. The motors will include brushless resolvers to permit excellent speed control or direct implementation of nonlinear compensation schemes. The motors will be controlled serially and will have microprocessor front-ends that will allow them to be controlled in torque or speed. Initial tests of the components show that a full microcomputer, including the crystal clock, can be included in the pressure-tolerant controller electronics.

Power

Summaries of the ABE power budget are contained in table 1.

ABE will use three different battery power systems during its development. Each of these battery types is well known to the oceanographic community and has proven to be safe and reliable when used correctly. For initial testing, gelled electrolyte lead-acid secondary cells will be used, as they can be conveniently recharged. For moderate duration survey work, alkaline primary cells can be used. For longest duration missions, lithium primary cells will be employed.

All batteries will be placed in the main instrument housing for ease of access and replacement. Total volume for batteries will be 22000 cm³, which will accommodate to 1 kilowatt hours of lead-acid cells, 2.2 kilowatt hours of alkaline cells, or 10 kilowatt hours of lithium cells.

Sensors

To succeed at even the most basic level, ABE must have adequate sensing of position and heading, a good video system, and must make basic physical water measurements. While demanding for a low power, full ocean depth vehicle, these capabilities are available or in the advanced development stage for other systems.

The primary sensor locations are on the nose of the main pressure housing and along the keel. In addition, cameras will be placed in the nose of the buoyancy pods. To preserve the low-drag character of the vehicle, cabling will be routed inside fairings and struts as much as possible.

The video system will initially consist of three CCD cameras, two monochrome and one color. Figure 3 shows the anticipated photo coverage for the vehicle when configured for general optical survey. The strobes will be placed as far aft as possible, which is the best possible geometry in this
circumstance [5]. Overlap in the water column between the strobe beam and water volume be-
tween the bottom and the camera has been minimized, decreasing backscatter. However, ABE’s
short length and limited strobe power will probably prevent imaging at altitudes of more than a
few meters.

TABLE 1

<table>
<thead>
<tr>
<th>ABE VEHICLE SPECIFICATIONS</th>
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<tbody>
<tr>
<td>1. Summary: Low power, long life, reliable, performs repeated surveys</td>
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<tr>
<td>2. Duration: Six weeks initially, extendable to one year</td>
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<tr>
<td>3. Maximum operating depth: 6000 m</td>
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<tr>
<td>4. Maximum speed: Two knots</td>
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<tr>
<td>5. Standard cruise speed: One knot</td>
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<tr>
<td>6. Total Survey Distance: At least 30 km</td>
</tr>
<tr>
<td>7. Total Survey Time: At least 50 hrs.</td>
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<tr>
<td>8. Translational control: Active in surge, sway, and heave</td>
</tr>
<tr>
<td>9. Attitude control:</td>
</tr>
<tr>
<td>- Heading: By thrusters</td>
</tr>
<tr>
<td>- Roll: passive</td>
</tr>
<tr>
<td>- Pitch: Combination of passive, moveable ballast, thrusters</td>
</tr>
</tbody>
</table>
| 10. Long range acoustic nav: range + 5 m, bearing + 2 degrees for ac-
    quiring subsea beacon and long range tasks |
| 11. Short range navigation net |
| - One year life |
| - Two cm repeatability |
| - Four updates/sec |
| 12. Minimum acoustic command and control: |
| - Interrogate status |
| - Abort |
| - Program select |
| 13. Surface navigation: ARGOS beacon |
| 14. Emergency subsea navigation: 12 kHz independent transponder |
| 15. Max propulsion power: 200 watts |
| 16. Vehicle navigation and control power: 10 watts |
| 17. Science power: 10 watts |

Measurement of the water physical properties such as temperature, conductivity, and optical opac-
ity will be made using conventional methods. For these measurements, the principal uncertainty
lies in the longevity of the conductivity measurement, but appropriate sensors are currently under
development outside of the ABE effort.

ABE will be navigated using a high frequency (300 kHz) transponding long-baseline acoustic
navigation system. This data will be used both to record and control the trackline. Expectations
for the system performance are contained in table 1.

Vehicle heading will be estimated using several sensors. ABE will carry a fluxgate compass to
measure magnetic heading and an angular rate sensor to help produce a high bandwidth estimate.
Additionally, the navigation net will be interrogated alternately from responders on the bow and
stem of the vehicle, which will provide a low bandwidth heading measurement aligned with the
navigation net and free from magnetic disturbances.
Computer System Design

The ABE computer system must meet a rigorous set of requirements. It must be compact and it must meet stringent power specifications, particularly during the sleep mode. The computer must have substantial floating-point power to implement navigation, trajectory generation, and control functions. From a software perspective, an efficient real-time, multitasking infrastructure is required. Both hardware and software should be expandable to accommodate more complex sensors and missions. From a development point of view, the system should transition gracefully from a tethered debugging configuration to untethered operation.

After a review of the available options and the development paths chosen by other groups building related systems, a hardware architecture was chosen. The system is distributed, with nodes communicating serially at 9600 baud, as shown in figure 4. Each node contains low powered single chip microcomputers (68HC11), but several of the nodes also contain additional computing power implemented with transputers (T800). The transputers also communicate directly with each other using their native high-speed serial capability (10 Mbit/sec). In general, each sensor and actuator will contain its own microcomputer for both communication and low-level processing. For example, each sensor will return data in engineering units, while motors will contain speed or position servos when appropriate.

As shown in figure 4, there are 4 serial busses in the preliminary configuration, 3 are 9600 baud lines and 1 is a transputer link. The top controller (labeled ABE) is implemented on a 68HC11 and

Figure 3. Anticipated photo coverage for ABE. Limited camera-to-light separation and limited strobe power will require low altitude optical imaging.
uses one of the low speed links to issue commands and to collect data. The ABE node can also communicate with the nodes labeled NAV and CON, which utilize transputers for the floating-point intensive navigation and control tasks. When the vehicle is in sleep mode, the transputers on NAV and CON will be powered down to save energy, but they can be brought on line with a serial command from ABE. Both NAV and CON have their own low-speed serial busses dealing with navigation sensors and thruster motors, respectively. When NAV and CON are powered down, their serial interfaces pass commands from ABE down to the sensor and thruster low-speed busses. When active, NAV and CON can also communicate at high speed using a transputer link. When increased floating-point power is needed, NAV and CON can easily be extended through the additional transputer links.

Figure 4. The ABE computer architecture will accommodate very low power operation (10 milliwatts) during the sleep phase, but also will permit substantial floating-point power to be brought on-line when needed through a transputer network. The transputers also provide a straightforward software and hardware mechanism for expansion.

While it is modest in computing power, the ABE node is the master device controlling the entire system. It is always powered up and keeps track of time, constantly monitors vehicle integrity, and can receive simple commands through an acoustic link. It will contain the highest level description of the mission plan, such as when to perform a particular survey, the sequence of movements for that survey, and the sensor sampling and logging strategy. The ABE node can also power the transputer nodes up and down. In the sleep mode, the ABE node can periodically power
up sensors and interrogate them for integrity, check the surrounding environment and log the data. Likewise, the ABE node can also check the thrusters and can turn them on occasionally to prevent seizing of bearings or biofouling of the propeller.

The imaging data dominates the data logging system design for ABE, with each image containing about $\frac{1}{4}$ Mbyte before compression. Given a goal of cycling all three cameras every 2 seconds, this presents a difficult challenge both for transfer rate and for total capacity. Off-the-shelf mass storage devices such as conventional disk drives, tape drives such as Digital Audio Tape (DAT), and optical disks are being considered for this role. All appear sensible in terms of power and size. Transfer rate considerations favor the disk drive, while capacity is superior with the tape units. Other scientific and vehicle data can easily be accommodated in the data stream to the logger.

A distributed control system similar to the the ABE computer system has been successfully tested using a tethered ROV in a test tank [6], and tests with an exact copy will begin soon. The tests to date have validated the hardware approach and provided valuable experience with the C language development environment for the transputers and the assembly language environment for the microcomputers. While assembly language is appropriate for nearly all the microcomputers due to their limited function, a high level language environment for the ABE node is necessary. We have chosen Forth for this component since it is optimized for quick mission program development. An ABE simulator running in a desktop computer will allow the user to test his new Forth code by putting a software model of ABE through the entire mission.

**CONTROL SYSTEM DESIGN**

As ABE will function unattended for extended periods of time, the reliability of its control system will be as crucial as the reliability of the sensors, computing hardware, and mechanical systems. Despite the rigors and uncertainty of the environment, experience with fixed instruments, manned submersibles, and ROV's in the deep ocean indicates that the most uncertain element is the vehicle itself. A control system that can automatically diagnose problems, correct them if possible, but know when to give up entirely is therefore primary for ABE.

The control system design task is simplified dramatically by the preliminary mission scenarios for ABE. ABE will not have a detailed internal representation of the environment. The area will be presurveyed and safe tracklines preplanned based on a balance between scientific yield and vehicle safety. Likewise, a prescribed sensor sampling strategy will be determined ahead of time. From a mission execution perspective, the first generation ABE will be programmed like an industrial robot of modest intellect, it will execute a sequence of paths and sample data with a preset schedule. Mission planning and execution software must be included that allows the scheduling of trajectory segments and sensor sampling as well as contingencies for failures.

Given that the mission is predetermined, the principal challenges in the initial ABE control system design lie in dealing with the uncertainty in the dynamic properties of ABE and the environment. Some of ABE's sensors or actuators may degrade or even fail during the course of a mission. Likewise, the environment can change unpredictably, as vent fields can contain currents with both vertical and horizontal components. ABE must automatically compensate for the unexpected changes or be able to determine when compensation is beyond its capabilities. When compensation is not possible, ABE may wait for better conditions (i.e. the current subsides) or it may abandon the entire mission and render itself safe until a recovery command is received (i.e. insufficient thrusters remain in working condition).
Recent results with a tethered vehicle in a test tank [6] show that nonlinear adaptive control methods based on sliding control [7] show promise for solving these problems. Based on Lyapunov stability criteria, the control system can accommodate a prescribed level of dynamic uncertainty due to factors such as imprecise modeling, but automatically adapt to changes that reflect changes in the model beyond the prescribed limits. In the recent tests [6], the the adaptive sliding control system could detect changes in control gain on multiple degrees of freedom, automatically refine the vehicle model until performance achieved a level corresponding to a prescribed level of model uncertainty, then automatically revert to a nonadaptive configuration. Moreover, a model of the new dynamics is explicitly formed which can be used to determine whether the change is too great to permit the mission to continue. These methods will be appropriate for dealing with the most common dynamic problems anticipated for ABE such as thruster degradation or failure, buoyancy changes, and currents.

Following success with deterministic surveys, future ABE missions will extend to far less structured tasks. These include lagrangian drift measurements in hydrothermal plumes, efficient mapping by following chemical or thermal gradients, and event-driven surveys based on measurements from complementary sensors such as tomographic arrays, acoustic doppler velocimeters, or ocean bottom seismometers. However, there is little chance of success for these types of tasks until the system can be proven reliable for well-described, deterministic surveys. The computing environment on the vehicle can be expanded directly by adding more transputer elements. The software architecture for implementing higher level control for unstructured tasks is the subject of lively debate within the mobile robot [8,9] and AUV community [10,11,12], and ABE will accommodate the most appropriate one when needed. The hardware interface between ABE and its top level controller (the ABE node) is limited to a serial line and subsystem power controls. Updating to an advanced controller will thus have minimum impact on the hardware.

CONCLUSION

The Autonomous Benthic Explorer (ABE) is an autonomous vehicle for scientific full-ocean depth survey. This paper reviews the motivation and design of the vehicle system and also discusses preliminary missions. The design for an initial version of ABE is nearly complete, and subsystem testing is underway.

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