DESIGN AND DEPLOYMENT OF A 3D AUTONOMOUS SUBTERRANEAN SUBMARINE EXPLORATION VEHICLE

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ABSTRACT

The NASA Deep Phreatic Thermal Explorer (DEPTHX) project is developing a fully autonomous underwater vehicle intended as a prototype of the Europa lander third stage that will search for microbial life beneath the ice cap of that Jovian moon. DEPTHX has two principal objectives: First, to develop and test in an appropriate environment the ability for an un-tethered robot to explore into unknown 3D territory, to make a map of what it sees, and to use that map to return home; and second, to demonstrate that science autonomy behaviors can identify likely zones for the existence of microbial life, to command an autonomous maneuvering platform to move to those locations, conduct localized searches, and to autonomously collect microbial life in an aqueous environment. The concept and prototypes are being tested in an unusual terrestrial analog that presents many of the likely morphologic regimes where life may exist on Europa: the 300-meter-deep (or more) hydrothermal cenote of Zacatón, Mexico, which contains diverse microbial mats, but remains uncharted, both spatially and biologically. In this presentation we summarize the final vehicle architecture and control systems approach to autonomous exploration in fully 3D environments in which apriori knowledge of the environment is non-extant and for which there exists no external navigation system. The latest field work at Cenote La Pilita will be presented describing the February 5, 2007 mission during which DEPTHX became the first fully autonomous cave exploring robot.

1. Overview

DEPTHX is a prototype AUV (autonomous underwater vehicle) for developing and testing two of the most critical capabilities that will be needed by the Europa lander third stage. These two advances are essential to the success of the Europa mission. To review quickly, the Europa mission architecture will likely include the following components:

• the parent spacecraft, which will remain in orbit either about Jupiter or about Europa and which will primarily serve as a data relay back to Earth from the Lander.

• the Lander, which will be a 3-stage device:

Stage 1: the physical landing system that will contain propulsion systems, power, and data relay systems to communicate with the orbiter, and which will control and carry out the descent and automated landing on the moon.

Stage 2: the “cryobot” second stage, which will melt a hole through up to ten kilometers of ice cap before reaching the sub-surface liquid ocean. Although the design is far from completely defined, the concept will most likely involve a nuclear powered thermal melter that will be attached to the bottom of the third stage. It is highly likely that the second stage will also deploy an armored fiber optic bundle behind it as it melts deeper. The fiber bundle will be frozen into the ice after the melter passes through with the third stage and will provide the communications link to the surface lander;

Stage 3: by far the most sophisticated element of the entire mission will be the lander third stage. In fact, the lander third stage will likely be a multi-stage device itself, roughly along the following lines: the melter tip from the second stage -- really just a shield and a sophisticated heat exchanger -- will likely be jettisoned upon reaching the subsurface ocean. The remaining vehicle will detach from the fiber optic system and will leave behind a powerful communications and navigation beacon as well as a rechargeable power pack. At that point what remains is the lander third stage proper: a novel, fast-moving cylindrical-shaped AUV that will be propelled by the nuclear power plant. The “fast mover” will carry a collection of redundant, electrically powered self-mobile smart sub-payloads that are sensor-rich devices.
capable of not only mapping into unknown territory and bringing the fast mover back to the navigation beacon at the bottom of the melt hole, but also able to “sniff” for indicators of environmental variables that might indicate the presence of microbial life and steer the combined 3rd stage vehicle towards those sites. At that point one of the smart sub-payloads will be deployed and will “fly” off in pursuit of microorganisms. To find them it will have to employ a multi-stage (hierarchical) detection system that improves the odds of finding something at each stage. Ultimately, using these tools, and if successful, it will detect and characterize microorganisms (most likely Bacteria or Archaea) in the Europan ocean and return to the fast mover, which will then drive it back to the navigation beacon whereupon it will upload what it finds to the surface lander, which will then relay the info back to the orbiter, which will then relay it back to Earth.

DEPTHX, then, is a prototype for the smart sub-payload of the 3rd stage fast mover.

The purpose of DEPTHX was to test the following two hypotheses:

1) can we design a fully autonomous underwater vehicle that can explore into completely unknown territory, create maps of that unknown territory in three dimensions, and use those just-created maps to return itself “home” without any other navigation aids?

2) can we design a fully autonomous science system that will seek out places where there is a high likelihood of microbial life and make a decision to collect samples that will demonstrate, unambiguously, that science autonomy is feasible on Europa. Specifically, can we demonstrate that by tracking environmental sub-aqueous variable gradients (temperature, chemical concentrations etc), along with spectral (color) differentiation, we can improve the likelihood of machine detection of microbial life.

These two capabilities form the fundamental underpinning of the success of the Europa mission, and thus became the focus of the DEPTHX field missions, the results of which will be described below.

2. DEPTHX Vehicle Design

The vehicle design morphed dramatically during the course of the project and it will be worthwhile here to summarize how we arrived at the final design. Initially, the thinking had been to canabalize a commercial ROV chassis and add science and navigation instrumentation to that platform, mainly to cut costs and speed schedule. This initial design [Stone et al, 2005 UUST05] involved the use of clustered banks of sonar transducers with three clusters of 8 serving as forward, port, and starboard obstacle avoidance arrays and a single lateral-looking barrel sensor that was to be used for map building. A commercial ROV is not a very hydrodynamic device and an exterior “hydroshell” was envisioned to cover the active components to both reduce drag and to minimize the likelihood of a snagged vehicle during actual exploration in a labyrinthine overhead environment of the type that was anticipated at the Cenote Zacaton test site as well as in the ice cracks in the surface crust of Europa. Figure 1 shows the “potato”, a second-generation concept in which the sonar clusters are un-grouped and the discrete transducers are mounted on the surface of the hydroshell, with shielded co-ax cables carrying the signal to a common digital signal processor array. This design began to approach the idea of a flexibly-deployed low profile sensor system in which the bot could approach near 4π steradian viewing. The op-
reative word is “near”. In the potato design there still had to be a propulsion system and this occupied the stern of the craft, as in traditional ROV design, since in fact we were still thinking of an ROV chassis on the inside of the potato shell.

This remained the design through the spring of 2005 as hardware and code preparations for the May 2005 field campaign to Zacaton dominated work on the project. The express purpose of that expedition was to obtain early real (noisy) data from Zacaton in a format that would allow testing of the crucial SLAM algorithm in the context of a vehicle-created 3D point cloud from the actual test site. While at Zacaton there were a number of discussions about how the system was actually going to work on an exploration mission. The Drop Sonde developed for the May 2005 expedition [Stone et al, 2005 UUST05] utilized the original barrel scanner concept for map building. The data coming in from Zacaton, however, began to evidence weaknesses in the line of sight limits for a purely planar array in attempting to provide real-time maps in 3D of the vehicle environment. A number of potential array concepts - spring boarding off the breakthrough potato skin idea - were sketched out at Zacaton. All of the sketches had the common concept of providing true $4\pi$ steradian viewing (for the moment we left out the issue of propulsion). Later simulation in the context of the SLAM algorithm [see Fairfield et al 2005, 2006, 2007] in representative 3D labyrinthine environments favored one design that came to be called the “three Great Circle” concept. On paper there were three orthogonal, intersecting planes and one could envision the intersection of those three planes lying at the center of a sphere. The lines on the sphere penetrated by the planes produced the “Great Circles” and it was on those lines that the discrete sonar elements would be placed. In this design the concept of “mapping” and “obstacle avoidance” sonar became blurred and all sensors could be piped to both code segments through a publish-subscribe data system.

During June of 2005 the initial design concepts gelled for a vehicle that incorporated this sensing approach in a compact geometry that had effectively no “stern” or “bow” and could therefore maneuver in any direction should it enter a blind corner in a sub-surface setting. Figure 2 shows a later version of this in July of 2005. Considerations for the placement of horizontal thrusters resulted in an equatorial band of thrusters with one in each quadrant, allowing any two to fail and yet preserve translational and rotational control of the vehicle. In Figure 2 the purple colored sonar units are 200m 2-degree beam elements, for long range obstacle avoidance, while the blue transducers are 100m range sensors. The placement of the thrusters on the equator forced the X-Y plane imaging sonars to be shifted off the centroidal plane.

The concept shown in Figure 2 lended itself easily to the idea of an exterior hydroshell comprising a snag-free ellipsoid of revolution (see Figure 3). The “M&M” design suffered from one serious flaw - the mass estimates for the overall vehicle were coming in at 1.5 metric tons. This required more “syntactic” (glass sphere epoxy foam) flotation than was feasible.

Figure 2: Great Circle framing concept was driven by SLAM imaging requirements. Purple elements are 200 m range sonar transducers; blue are 100 m transducers.

Figure 3: Great Circle frame system embedded inside elliptical “M&M” hydroshell - August 2005. The open rectangle accepts the modular science payload.
within the geometric constraints of an absolute ellipsoid. Further, the viewing angle for the return sonar pulse required a 15 degree clear cone in front of each transducer to reduce multipath. These constraints led to the adoption of four expanded ellipsoidal quadrants on the top side of the vehicle, as shown in Figure 4.

From a systems debug viewpoint we needed a design that permitted all of the vehicular electronics and control systems to be accessible while still connected to the rest of the vehicle. This is frequently accomplished in ROV and AUV design with swing-out housings that permit a bell-shaped pressure housing to be swung out of the vehicle and removed, leaving the end plate, with it’s electronics interface cables still attached, connected to the vehicle. We spent considerable time working this problem before arriving at the solution shown in Figure 5 and 6. DEPTHX has
11 separate pressure housings and the constrained, non-orthogonal geometry creates both limitations and advantages that are distinctly different from traditional AUVs and ROVs, but which are very much required by the scenarios likely to be encountered in a Europa sub-ice crack exploration scenario. The service depth rating for the entire vehicle is 1,000 m, making it a significantly robust design that will have access to many interesting biological sites on Earth after the Zacaton field campaign has been completed - most notably, the successor to DEPTHX, known as ENDURANCE, has been approved for development with ultimate deployment to Lake Bonney in the Taylor Dry Valley in Antarctica in fall 2008. The 1,000 m depth rating comes with a price: the average weight of each bell dome is in excess of 50 kg. Taking this into account and considering the sensitivity of every oring re-seal (that is, the risk of shearing an oring anytime you re-assemble the system after initial hydrotest), we opted for the vertical loading configuration shown. This permits overhead hoist removal of individual domes and allows for precision re-fit should (when) electronics need maintenance or repair. The syntactic buoyancy quadrants are likewise designed for direct vertical removal.

The entire vehicle was modeled in Solid Works 2006. The overall diameter (major ellipsoid axis) is 2.13 m and the height (ellipsoid minor axis) is 1.52 m. Structural analyses of housings that see full hydrostatic pressure, as well as all of the structural framing elements, were conducted using the Cosmos non-linear and non-linear buckling FEA codes. Individual housings and connecting cables (of which there are 96 external power and communications lines comprising 250 meters of cable and more than 400 electrical
conductors) were largely achieved using dry-mate connectors from Seacon. Figure 7 shows the wiring schematic for the overall vehicle.

The science mission for DEPTHX required the vehicle to be able to acquire both wall core samples and liquid samples from the water column. In order to do this without risking entrapment of the vehicle when approaching an overhung or jagged wall, an extendable probe was developed that was able to reach 1.5 m beyond the ellipsoid shell. Thus, the vehicle could come up to a 1.5 m safe standoff distance (as measured by the sonar arrays, which constructed a fitted plane from the geometric data in front of the vehicle to assess the safety of a wall approach), extend the probe, and obtain the needed samples. Sampling was able to be triggered by either the presence of an environmental variable gradient (we measured dissolved oxygen, pH, conductivity, dissolved solids, redox, temperature and sulphide) or changes in wall coloration, although during actual tests at cenote Zacaton the latter failed because there were no significant wall color changes in the anoxic zone of interest to the project scientists. The former (sulphide, in particular) was used as the basis for a science autonomy experiment described later). The probe system (Figure 8) was built by SwRI.

![Figure 7: DEPTHX System Wiring Schematic (simplified) comprises 96 cables and more than 400 conductors carrying signal, power, and comm. External umbilical block provides for vehicle servicing between missions. The umbilical block contains a magnetically operated master kill switch for emergency mission termination which can be readily accessed by both humans and rescue ROVs/submersibles. Fiber optic spooler and WiFi interfaces provide Ethernet 10/100 baseT comm as well as tele-op over-ride.](image-url)
3. Navigation and Control

DEPTHX employs two separate navigation systems. The primary system is based on traditional dead reckoning and uses as its primary input sensor data from a high grade IRU (inertial reference unit), a DVL (doppler velocity log), and high grade depth sensors (see Figure 7). In practice the DVL dominates the dead reckoning filter for X-Y translations (see Figure 9 for the vehicle-centric coordinate system nomenclature) and the IRU is used for position input only in the absence of data from the DVL, which can occur if the vehicle is less than 1 m from a target surface. The Z-coordinate (depth) is provided by absolute measurement from two Paroscientific depth sensors, which are normally averaged; a significant discrepancy between the two is grounds for a mission abort. Yaw (heading) is obtained from the RLG (ring laser gyro) portion of the IRU and is extraordinarily stable, exhibiting drifts of less than 0.01 degree per hour in isothermal conditions. The pitch and roll of the vehicle, as previously mentioned are substantially damped, leaving a 4 DOF vehicle.

Figure 8: Science package components on the DepthX vehicle

Figure 9: Vehicle-centric coordinate system for DEPTHX
The second form of navigation is based on full 3D geometrical mapping. Simultaneous Localization and Mapping (SLAM) is the process of building a map of the environment from sensor data, and then using that map to localize the vehicle. Most work in this area has been directed towards surface terrain following as well as tracking of flat hallways, with some work in sea bed tracking. All of these environments are essentially 2-1/2D in nature and much of the efforts thus far have depended on high resolution sensor data to enable feature recognition. In the underwater domain it is generally not possible to obtain the high resolutions needed for feature recognition unless the water is very clear, and such conditions cannot be counted upon for exploratory purposes given the risk involved in losing an expensive AUV. For complex 3D underwater environments an alternative approach needs to be taken.

3D-SLAM requires that the vehicle be able to simultaneously sense new geometry as it moves into unknown territory and yet also be able to look "backwards" into terrain for which a map is already extant. Because the orientation of the vehicle relative to the map cannot be predicted ahead of time the "geometry engine" of the vehicle needs to effectively view $4\pi$ steradians in real-time about the vehicle. This forces a different solution than is typically employed on ocean going AUVs where the predominant planform of the vehicle is torpedo-shaped and the typical compliment of sonars onboard consists of a downward or upward looking sidescan or multibeam unit and perhaps a forward looking wide beam obstacle avoidance transducer. An equally important consideration is the propensity for multipath spoofing in a 3D labyrinthine environment, especially for the above-mentioned traditional swath-type bathymetry instruments. We resolved both issues by using an equal-angle distributed array of very narrow beam transducers, mounted on three orthogonal great circle endoskeleton frames as shown in Fig. 5. The transducers were a mix of 200 m (330 kHz) and 100 m (675 kHz) 2-degree beam designs following the successful results reported in [Stone et al. 2000]. A total of 54 such 2-degree beam transducers generates a continuous point cloud about the vehicle. To the author’s knowledge, DEPTHX represents the first AUV designed from the ground up to implement 3D SLAM. What remains is to incorporate the geometric data into a real-time map.

For DEPTHX we have developed a data-driven representation of the environment in which we employ a probabilistic model that tracks a best estimate of the vehicle trajectory (pose) and a 3D map of the environment that follows the vehicle. In
order to implement 3D-SLAM there are essentially two problems that have to be solved: 1) to implement an efficient means of digitally modeling 3D maps of the world as seen by the vehicle sensor suite and 2) to solve for the best estimate at each instant in time for the vehicle pose and the state of the world map at that time. We achieve this using 3D evidence grids and particle filters, with some novel map storage using a special variant of octrees. The mathematics of this approach in DEPTHX were developed at Carnegie-Mellon and are described in detail in [Fairfield et al. 2005; Fairfield et al. 2006; and Fairfield et al. 2007] and will not be duplicated here. The vehicle is operated predominantly in velocity control mode. In pure dead-reckoning mode, the velocity controller takes its input directly from the dead-reckoning system; in SLAM mode, the SLAM algorithm uses the dead-reckoning system to estimate the next pose as the seed for the next optimization cycle. It’s output is sent to the vehicle pilot which then selects inputs to the velocity controller (see Figure 10).

As was described in the introduction, one of the primary objectives of the DEPTHX project was to demonstrate science autonomy. This required a hierarchical microbe detection strategy, first by looking for gradients in environmental variables, and later looking for color anomalies on surfaces. The latter explicitly requires the vehicle to perform proximity operations. DEPTHX achieves this using two specific behaviors: wall approach, and wall tracking. Both use velocity control. In the first, an approach to a target wall is made while maintaining heading and lateral drift. To do this a plane is fitted to the forward looking sonar data and the vehicle servos on that plane until achieving the target stand off distance. Once so initialized the vehicle can move up/down the wall or left/right along the wall at the designated standoff distance either in differential displacement control or in constant velocity mode, while maintaining an angular lock to the wall plane. Navigation and vehicular control are discussed in greater detail in [Fairfield et al, 2007].

4. Electronics

The DEPTHX LLIO (low level I/O system) was developed by Stone Aerospace and performs all of the direct hardware (sensor and actuator) interfacing, including driver development, sensor polling, motor control, variable buoyancy control, and composition of data packets to be published on IPC for the System Executive to process at a higher level. The LLIO, like the SystemExecutive, runs on Linux, kernel 2.6.9. The LLIO communicates with the sonar processors (both 100 m and 200 m), depth sensors, leak detection boards (see below), thrust controllers, DVL, IRU, Hydrotech environmental sensor suite, and the batteries. The leak detection and thruster control boards (custom developed for DEPTHX) communicate with the SystemExecutive processor via the CMU IPC communication protocol providing end to end data connectivity. External communications can be maintained throughout a mission through an optional TCP/IP connection over single mode T1 cable. The fiber optic cables (actually 1 mm strands) were particularly useful during the debug and code development stage of the AUV since they allowed the code development teams to “look over the shoulder” of the vehicle using special 3D viewers driven by real-time data.

There are some 36 processors on DEPTHX. The vast majority of all inter-device data transfer is accomplished via serial communications using a number of protocols which are driven by the available smart sensors and actuators. The vast majority of data transfer is accomplished using RS485 protocol but there is some USB, one ARINC-429 interface (for the IRU), and several 10/100 Ethernet links. The primary vehicle computer is an industrial cPCI controller rack from Kontron with three cpu boards, a serial I/O card, Ethernet card, and inline power supply running off telcom voltage (48-60v). Most of the periferal processing is handled either on PC104+ stacks or custom-designed embedded systems and sensors.

5.1 Power

We chose to employ a parallel battery system for redundancy and capacity (Figure 11). Power consumption for all systems was determined and a typical mission “power use profile” was modeled and a tally of the total energy required was calculated to be in the 4 to 5 kW-hr range. The model included simple hydrodynamics, propulsion efficiencies, and anticipated hotel load (all internal electronics normally on during a mission) due to all on-board systems. The vehicle was typically programmed to return home after depleting 30%-40% of its energy supply. This fact, coupled with the energy needs noted
above, set our total battery capacity target to be in the 6 kW-hr range.

Different suitable battery chemistries were explored before settling on Li-ion. PowerStream Technologies was selected as the Li-ion vendor. Each pack consists of 13 cells in series, resulting in a 48 volt, 60 Ahr, 3 kW per pack for a total of 6 kW of power. Testing was conducted for charge/discharge cycles. The packs when new and fully charged will store about 3.2 kW-hr of energy. But imbalanced discharge during actual field exercises and non-optimal charge cycles led to actual available power being approximately 2/3 of the nominal full value. Great efforts were undertaken to deal with the monitoring of individual cell voltages, using cell balancers during charging, and developing high power disconnect systems so that the system could isolate a battery in an emergency (E-stop). Battery state information was (voltage in each cell, current draw, temperature) was uplinked to the SystemExecutive during a mission and was frequently the grounds for a fault trigger and mission abort.

Power distribution was through size 10 AWG cables to the propulsion system and through size 14 AWG cables to the main computer system (and subsequent distribution to all other system), for each battery. Every pressure vessel on board has a DC to DC converter to convert the battery voltage to the appropriate voltage for that system.

5.2 Propulsion

The propulsion system consists of six thrusters and a Variable Buoyancy System, although the latter was only used for a few field trials as we discovered that fine trimming was generally sufficient given the stiffness of the syntactic and electronics housings. The thrusters are configured in pairs, two pairs in the horizontal plane (X any Y axes) and the third pair aligned with Z axis (vertical). This gives significant redundancy in that any two horizontal thrusters (or any one of the vertical thrusters) can be lost while still maintaining authority and control over the vehicle. Simple hydrodynamic modeling of the vehicle was used to determine the basic thruster requirements. Additional considerations such as efficiency, ruggedness, and cost were considered. Deep Sea Systems International was chosen as the

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**DepthX Power Architecture**

![Diagram](image)

Figure 11: DEPTHX Power Architecture. Primary line voltage is standard telcom.
The thrusters were supplied with MTS motor controllers. These controllers are highly configurable and interfaced with the main computer through an RS485 link. The MTS controller was operated in torque control mode with speed (RPM) as feedback. The maximum power consumption for the propulsion system was \( \sim 1.5 \) kW (including losses). This is a peak value and cannot be sustained due to thermal issues. The maximum continuous power (limited by thermal issues) is estimated to be between 400-500 watts. The thrusters operate at 100 VDC, so we employed Vicor DC-DC step up converters. Two Vicor units were used for redundancy, each unit powering one thruster from each axis. Other than some minor fluid leakage from the PBOF oil compensation system, there were no maintenance issues with the thrusters throughout the entire DEPTHX field test program.

5.3 Leak Detection

One of the paramount abort scenarios for an AUV is the self-diagnostic regarding the breach of water into one of the pressure housings (there were 11 on DEPTHX). Catastrophic seal failure will be extremely low, given that each individual housing with their relevant electrical and pneumatic penetrators in place was hydro-tested to 1,000 m hydrostatic pressure prior to field deployment. However, routine maintenance access to the electronics can lead to minor degradation of oring seals over time and those leaks are slow and pressure dependent. Having a means to detect a slow leak and auto-terminate a mission was a required feature, since full flooding of more than one housing would lead to a negative buoyancy situation that would tax the vertical egress systems.

Off the shelf designs were unacceptable because of either unacceptably high power consumption, or because they required the presence of sufficient liquid water to allow a probe to be shorted. Stone Aerospace developed a custom design that uses a surface mount sensor to detect changes in the relative humidity of the gas in the pod. As the pods are flushed with dry nitrogen prior to being sealed, the RH should remain very close to zero during the mission - and in fact most remained in the 0-5% RH range throughout the entire project. The notable exception was the battery pods which, despite frequent dry nitrogen purging (every time we charged) the RH was difficult to maintain below 15-25%, even with bag dessicant freshly installed. The consensus was that the batteries themselves may be generating some moisture on discharge, though no formal test program to prove this was undertaken. A photograph of the LDPCB (Leak Detection Printed Circuit Board) is shown in Figure 12. One LDPCB was included in each pod of the Depthx vehicle. The LDPCB communicates over a multi-dropped RS485 communications link to the SystemExecutive computer. Up to 16 devices may be on each logical communications link. The LDPCB also has a multitude of analog and digital inputs and outputs, including power relays that are suitable for switching large loads. Thus, the LDPCB was also used as an optional means of cycling power to the pods.

6. Field Results

The preliminary field investigation for the DEPTHX project focused on deployment of the AUV into the Poza la Pilita cenote, located on Rancho la Azufrosa, in Tamaulipas, Mexico, about 6 hours travel south of Texas. La Pilita has an entrance diameter of 20 m and was only known by sport divers who descended to a depth of approximately 100m on a vertical line. Visibility is limited and so no knowledge was available as to the extent of the cave nor whether there were any horizontal tunnel extensions, such as are common in the cenotes of the Yucatan near Cancun, for example.

![Figure 12: DEPTHX Leak Detection PCB was custom designed to resolve several outstanding AUV problems.](image-url)
Figure 13: Field operations at Rancho la Azufrosa, Tamaulipas, Mexico in 2007. Counterclock from Upper Left: Zacaton Mission 1 Team (from left: Marcus Gary, Bill Stone, Tom Lyons, Ian Meinzen, John Kerr, Nathanial Fairfield, Dom Jonak, Dave Wettergreen, George Kantor, Vickie Siegel); Lowering the bot into cenote Zacaton; View from the water surface; John Kerr loading charged Li-ion battery stacks; Vickie Siegel performing sonar maintenance; Rolling the vehicle out from the hanger for another day’s testing.
We conducted approximately a dozen separate autonomous robotic missions in La Pilita in February and March of 2007. Half of these were for the purpose of testing SLAM navigation. Starting with no prior map of La Pilita, DEPTHX verified the depth to be 100 m, but more importantly constructed a complete 3D map of the cave without human intervention. The robot subsequently returned to the entrance using this map to within 15 cm of its starting position, despite having been underwater for as much as 4 hours (see Figure below). Thus, the exploration of La Pilita represented the first autonomous exploration of a subterranean cavern by a robot.

In order to test the science autonomy capabilities of DEPTHX water and wall sample collections were made in both La Pilita and Zacaton to characterize organisms at a particular depth so as to minimize cross contamination. The robotic sampling arm and triggering system worked autonomously and this basic pattern was applied at various depths and locations to characterize the varying environmental conditions and biologic activity. Unfortunately, what DEPTHX discovered was that the environment was... boring. Most sensor data showed insignificant variation in more than 300 meters of depth. The sole exception was the sulphide level, which climbed very gradually with increasing depth. Coloration of the walls of the hydrothermal spring also proved to be boring - a monochromatic orange-brown from just below the photic zone to the maximum depths reached by the bot (see top right image in Figure 15).

Some of the most complicated missions took place in Cenote La Pilita. In repeated dives DEPTHX ran untethered down to 40m depth then maneuvered 30m horizontally under the ceiling of La Pilita to ascend into a dome at 30m depth (this can be seen in the profile map shown at bottom right in Figure
Figure 15: **Top Left**: The DEPTHX research robot with its science probe extended, preparing to approach the wall at Cenote La Pilita.

**Top Right**: The solid core sampler sub-system on DEPTHX milliseconds after acquiring a 1 cm diameter sample from the wall of cenote Zacaton at 114 m depth on May 17, 2007.

**Center Left**: DEPTHX onboard wide field camera used to track color changes on the wall of the cenote -- color changes usually mean the presence of microbial colonies.

**Bottom**: The DEPTHX science probe, an extensible 1.5 m arm used for taking wall core samples, water samples, and for wall imaging and color tracking. Key components are labeled on the photo. The science payload and probe was developed by SwRI.
There it automatically located the wall, moved in to 3m, extended its sampling arm. It flew toward the wall until the coring mechanism was in contact and while the robot held position, it took a core sample while recording video and drawing a water sample. The rover then backed off, retracting the arm and then dove down, out from under the dome and returned to the surface. This was executed autonomously without a tether, so the results were known only after the rover returned to the surface and the data examined. Eventually samples were collected throughout the La Pilita cenote and, as well, to depths of 273 m in cenote Zacaton. The samples are being analyzed by John Spear at the Colorado School of Mines. DNA extraction has already revealed several kinds of bacteria that live at that depth, many of a kind previously unknown. To date, we have limited analysis completed, but we have generated a map of the site, as well as understand the chemistry of the water. The findings show that both cenotés are quite homogeneous in nature, interesting in that they represent large bodies of water with little chemical change throughout.

DEPTHX successfully, and autonomously, mapped both Cenote La Pilita and Cenote Zacaton in three dimensions. The data for these maps are available from the author. Perhaps more than anything else, the data reveal graphically what was, until 2007,
completely unknown territory inside the planet. Combined they represent a unique data set that helps explain the functioning and extent of hydrothermal springs in Mexico.

Given the successful tests of autonomous mapping and SLAM, what remained was an unambiguous test of the science autonomy capability. We had, in the process of collecting the core and water samples in Zacaton and La Pilita, been exercising elements of the automated systems, but had not strung them all together. Complicating the matter was the previously described homogeneity of the environmental variables and the coloration of the wall surfaces. There was a slowly increasing trend in the concentration of sulphide below the level of the photic zone, but nothing like the initially hypothesized (and hoped for) sulphide plume rising from a vent in the wall of the spring that would have triggered autonomous tracking behavior. An arbitrary concentration of 0.042 ppm was selected as a trigger threshold for initiation of autonomous sample collection. On May 26, 2007 DEPTHX descended into cenote Zacaton, mapping along the way and maintaining a centroidal XY position for safety. At a depth of 114 m it detected the sulphide threshold and began maneuvering towards the wall, entered into proximity operations, extended the probe, and impacted the wall using previously tested automated core sampling procedures. It then initiated its nominal egress procedure and returned to the shaft centroid for ascent. The critical portion of the mission is shown in the left hand computer-generated playback frame in Figure 17. The thin yellow trace is the vehicle trajectory, which clearly shows the sudden detection of the sulphide threshold and the decision to traverse laterally to the wall at that depth. The orange dots are individual sonar wall hits. The right hand image in Figure 17 shows sulphide data from a previous mission that identified the increasing sulphide vs depth trend, and shows the trigger threshold for initiation of sampling behavior.

There are, of course, many additional layers of science autonomy to be developed on the path to a Europa mission, but DEPTHX went a long ways towards building the foundation for that autonomous behavior.
7. Conclusions

DEPTHX achieved the two science goals that had been established at the outset of the project, despite the extraordinarily compressed time schedule and complexity of developing a 4DOF AUV from scratch. In the process of allowing physics and mathematics to drive engineering invention, a completely novel vehicle architecture emerged that was certainly not predicted from the initial thinking at the time the original proposal to NASA was written. The axysymmetric shell-of-revolution concept (DEPTHX was an ellipsoid) led naturally to redundancy in thrusters, ability to avoid snags in complicated terrain, and most importantly the ability to call any direction on the vehicle the “bow”. In a complicated situation involving entrapment with a few dead thrusters, DEPTHX could perform a yaw maneuver and be fully functional operating with only half its propulsion system. There were unexpected, and serendipitous consequences of going down this path. Because of the axisymmetric exterior, yaw maneuvers came at almost no cost -- once the bot was spun up it took very little energy to maintain that. Spinning the bot during a descending (or ascending) exploration mission turned the planar arrays of discrete tight beam sonars into the underwater equivalent of a scanning LADAR. What resulted was “spin mapping”, an extraordinary new and powerful technique for building full 3D maps in noisy, cluttered, multipath environments. The success of spin mapping was not confined to descents down hydrothermal springs with predominantly vertical morphology -- it also worked for building detailed maps of lakes and quarries. This latter capability will carry over into the ENDURANCE project, which is now beginning work on the next step on the path to mission to Europa. In late 2008 and 2009 ENDURANCE will map the sub-surface world of Lake Bonney in Taylor valley, with a little help from DEPTHX technology.

8. Acknowledgements:

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Team DEPTHX involved, at various stages, more than 30 researchers, engineers, software programmers, and three PhD students who are in the process of completing their degrees in relation to the project. Here is a terse summary of the participants and their various roles:

Stone Aerospace (principal investigator; vehicle design; system integration; low level control and sensing software; intra-processor networking; onboard navigation sensors, computers, and electronics; Li-Ion power sub-systems, propulsion and thruster controller sub-system; imaging and obstacle-avoidance sonar sub-systems; variable buoyancy engine; environmental sensing sub-system, structural framing; syntactic design; testing and evaluation; project management)

Carnegie-Mellon University Field Robotics Center (system executive and SLAM software, and science autonomy software)

Southwest Research Institute (science payload design, fabrication, and test; science payload software)

University of Colorado Boulder and the Colorado School of Mines (microbiology program lead; field microbiology, and DEPTHX sample DNA sequencing)

University of Texas at Austin (Cenote Zacaton field logistics; Mexican government permits; Mexican landowner relations; hydrogeology instrument payload support).

University of Arizona Lunar and Planetary Institute (science payload and vehicle design programmatic and technical review; strategic program guidance for path-to-mission planning).
Universidad de Nuevo Leon, Facultad de Ciencias de la Tierra (Dr. Juan Alonso Ramirez; analysis of geospatial data, geochemical and biological simples collected by the robot)

Universidad del Noreste (Antonio Fregoso; biological, ecological, and environmental field descriptions of subaquatic flora and fauna for the Cenotes “La Azufrosa”).

9. References:


