"DEPTHX - The DEep Phreatic THermal eXplorer: Robotic exploration and characterization of Sistema Zacatón on the mission path to Europa"

Session Chair: Marcus Gary

Description:

This two-hour special session presents results of the NASA funded DEPTHX project which developed and tested an autonomous robotic underwater vehicle as a prototype probe that would search for life on the frozen moon of Jupiter, Europa. Seven separate presentations from project scientists and engineers will cover topics including: engineering design, robotic mapping, scientific sensors, hydrogeologic applications, geomicrobial discoveries, future Antarctic exploration, and planetary ties to Europa.

The Search for Life on Europa

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Liquid water is not unique to our own planet, and the strategy of following the path to extraterrestrial water is likely to produce great discoveries, especially in the area of astrobiology. Reaching liquid water will involve not just landing on a target planet, but penetrating below the surface with technologies that will permit exploration and characterization of the aqueous environment. For example, Europa's global ocean lies below many kilometers of ice.

In anticipation of missions to explore of Europa's ocean, considerable planning and technology development has addressed the problem of drilling, melting, or punching through the thick ice with a variety of possible types of robotic penetrators and then exploring the subsurface ocean. However, the most interesting aqueous environments may be within channels of liquid through solid strata, such as where Europa's ocean may penetrate hot springs on its floor or tidal cracks in its surface ice. Those settings may provide conditions uniquely hospitable to extraterrestrial life.

Therefore, exploration will require development of autonomous vehicles with in situ analysis tools for probing such channels. The issues are quite different from those involved in drilling through solids or moving through wide-open submarine spaces. Moreover, technology for exploring confined channels may allow exploitation of cracks in Europa's ice to minimize the need for penetration of solid ice. It will also be useful within the thick oceanic layer, as well as in exploring any hot springs or other channels into the sea floor. In fact, it is likely that only such an intelligent autonomous search system is likely to have success in a Europan setting.

DEPTHX
DEep Phreatic THermal eXplorer

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The NASA Deep Phreatic Thermal Explorer (DEPTHX) project successfully developed 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 had 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 saw, 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 were tested in an unusual terrestrial analog that presents many of the likely morphologic regimes where life may exist on Europa: the deep hydrothermal cenote of Zacatón, Mexico, which contains diverse microbial mats, but which remained uncharted, both spatially and biologically, prior to the DEPTHX project. In this presentation we summarize the final vehicle architecture and control systems approach to autonomous exploration in fully 3D environments in which *a priori* knowledge of the environment is non-extant and for which there exists no external navigation system.

Robot Autonomy for Scientific Exploration in Flooded Caverns

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Autonomous robots can be powerful tools for scientific exploration, especially in extreme environments that are not accessible to humans. In this paper, we provide an overview of the navigation, control, and decision-making capabilities that allow the DEPTHX robot to autonomously conduct science missions in the cenotes of Sistema Zacatón. In the area of navigation, we will describe a novel algorithm for simultaneous localization and mapping SLAM) in 3D environments. This allows the vehicle to operate in previously unexplored environments by creating maps of cavern geometry while simultaneously using those maps to navigate. In the area of motion control, we will present a number of behaviors that we have developed for DEPTHX, including open water point-to-point motion, near-wall navigation, science sampling maneuvers, and emergency escape contingencies. We will also discuss the system executive that provides the architecture and decision-making framework to tie together the various navigation and control components to accomplish the desired science objectives. We will conclude the paper by presenting experimental results that demonstrate the mapping, navigation, and science operations executed in the exploration of Sistema Zacatón.

DepthX Science Payload

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The DepthX science payload includes the sensors, science computer system and sample collecting tools needed to demonstrate that the robot can explore and search for life completely autonomously. The approach is similar to methods used by field biologists to identify locations of interest and gather samples for analysis.

Water chemistry, including temperature, pH, salinity, conductivity and sulfide concentration is sampled to identify gradients or values indicating biological activity. More detailed examination of these regions is conducted by computer analysis of video images from two video cameras. The system also includes a pump to circulate water through a flow cell and capture video images from a microscope. Sequences of microscope images are analyzed to detect the motion and frequency of microorganisms and color images of wall surface are analyzed to characterize the color and texture of wall surface regions. Analysis software compares these attributes to a model of what is 'normally' observed in the environment to identify interesting regions.

When image analysis indicates signs of interesting biological activity, the DepthX computers direct the robot to collect samples. This is done with a hydraulically operated robot arm that can reach six feet beyond the edge of the vehicle. The robot arm carries a video camera, a tube for collecting water samples and a unique coring tool for collecting solid samples of algae mat or other growth on the wall. Water samples are collected in five different containers under control of the science computer. Water samples and solid samples are returned to the surface for analysis.

Sistema Zacatón: Hydrogeologic Discoveries from DEPTHX

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Sistema Zacatón is a unique karst system in northeastern Mexico and contains the world's deepest underwater shaft, Él Zacatón. Prior to the DEPTHX project, Él Zacatón and other nearby flooded sinkholes, called cenotes, had been explored by the expert cave divers of Jim Bowden, Sheck Exley, and Ann Kristovich; and scientifically investigated by the authors. Spatial data from the primary exploration and study was limited by the extreme depth and volume encountered in the cenotes of Sistema Zacatón. Él Zacatón was known to be deeper than 300 meters, and had been dove to 281 meters by Bowden in 1994 using SCUBA techniques. It was unknown if passages continued either laterally or vertically in any of the cenotes. The water chemistry had been documented by Gary and Sharp using surface-based and SCUBA sampling methods, but these measurements and samples were limited due to the immense size of the cenotes.

The DEPTHX probe is a superb tool to map the actual geometry of these dissolution/collapse cavities, determine if any passages or tunnels connected the cenotes, collect high spatial density water chemistry measurements, and collect water and wall samples from depths far beyond those possible with SCUBA methods. The high-resolution 3-D maps generated by DEPTHX showed that Él Zacatón reaches a maximum depth of 319 meters at the base of a northwest sloping floor. The cenotes Caracol and La Pilita have a "whiskey-jug" type morphology that relates to post collapse travertine precipitation in the upper zones. The flat bottom of Verde supports previous geophysical evidence that indicates paleo-water table over 45 meters below that of the present day. Basic water quality measurements of temperature, dissolved oxygen, specific conductance, and pH support previous observations that the warmer, deep cenotes are all homogeneous and well-mixed, likely due to convection driven by persisting hydrothermal energy sourced from nearby volcanic activity.

A Depth Profile of Microbial Diversity and Community Structure in Cenote Él Zacatón

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The microbial community structure of Cenote Él Zacatón was analyzed by 16S rRNA gene sequence analysis to determine how microbial communities change with depth in an extremely deep, freshwater environment. Samples from wall biofilms as well as from water column samples were collected by the deep phreatic thermal explorer (DEPTHX). Clone libraries were generated from samples collected at a range of depths (0m-273m) using primers specific for all three domains of life (Bacteria, Archaea, Eukarya). Phylogenetic analyses were performed to understand the taxonomy of retrieved sequences as well as the phylogenetic relationships to known microbial lineages. In addition, corresponding water samples were analyzed for anions, cations, metals, total organic carbon, Eh, pH, and specific conductivity to correlate with microbial community structure. Statistical software incorporating phylogeny was used to determine how changes in these chemical parameters affected the types of microbial lineages found at different depths.

Samples from shallow regions of the cenote revealed a dominance of phototrophic sequences primarily belonging to the bacterial division cyanobacteria. In addition, a number of sequences were obtained that showed close phylogeny with *Acidithiobacillaceae*, a genus of Bacteria containing known sulfide-oxidizing bacteria; these bacteria are likely oxidizing sulfide generated from sulfate reduction processes below. Samples from deeper regions of the cenote showed a diverse set of sequences that grouped with known sulfate-reducing bacteria in the bacterial class δ-proteobacteria. In addition, many sequences from deeper samples, from both Archaea and Bacteria, represent putative division-level novelty, suggesting that the geographical isolation and water chemistry of Zacatón have formed novel microbial lineages living deep within the cenote.

In general, the microbial diversity in Zacatón is incredible. Out of approximately 90 currently accepted bacterial divisions, more than 30 have been observed to date in Zacatón, by analyzing only ~600 16S sequences. An additional 6 putative bacterial divisions have also been found, but additional phylogenetic analyses will need to be performed to validate these findings. Additional sequencing from depth is expected to reveal even greater microbial diversity from all three domains of life.

Environmentally Non-Disturbing Under-ice Robotic ANtarctiC Explorer (ENDURANCE)

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Permanently ice-covered liquid water environments are among the leading candidate sites for finding evidence of extant life elsewhere in our solar system (e.g. on Europa and other Galiean satellites, and possibly in subglacial lakes on Mars). Furthermore, permanently ice-covered lakes
were likely the last refuge for life on the surface of Mars during climatic deterioration from an early warmer and wetter period. In order to have the proper tools and strategies for exploring the extant ice-covered planetary environments, and to have a better understanding of the Martian ecosystems, past and potentially present, we are developing an autonomous underwater vehicle (AUV) capable of generating for the first time 3-D biogeochemical datasets in the extreme environment of perennially ice-covered Antarctic dry valley lakes. The ENDURANCE (Environmentally Non-Disturbing Under-ice Robotic Antarctic Explorer) will map the under-ice lake dimensions of West Lake Bonney in the McMurdo Dry Valleys, and be equipped to measure a comprehensive suite of physical and biogeochemical indices in the water column, as well as Raman Spectrometry of the water column and benthos. The AUV is being specifically designed to minimize impact on the environment it is working in. This is primarily to meet strict Antarctic environmental protocols, but will also be useful for planetary protection and improved science in the future.

We will carry out two Antarctic field seasons (in concert with our NSF-funded Long Term Ecological Research) and test two central hypotheses: H1: The low kinetic energy of the system (diffusion dominates the spatial transport of constituents) produces an ecosystem and ecosystem limits that vary significantly in three dimensions. H2: The whole-lake physical and biogeochemical structure remains static from year to year.

The talk will provide an overview of the ENDURANCE project and an update on the AUV development.