

EXPLORING MINIATURIZATION LIMITS FOR AN INSTRUMENTED AUTONOMOUS SUBMERSIBLE EXPLORER FOR EXTREME ENVIRONMENTS

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Abstract

The Miniature Autonomous Submersible Explorer (MASE) is a vehicle concept developed to probe the current miniaturization limits on instrumented autonomous submersibles. The goal of the concept is to develop an extremely small vehicle that carries MEMS instruments used to seek science data in extreme aqueous environments relevant to astrobiology. The vehicle's focus on extreme miniaturization allows it to fit inside other vehicles or to be taken to places previous larger vehicles could not venture. The vehicle is outfitted with features like autonomous control, real time science data processing, high-speed full-duplex optical fiber tethered communication, high-resolution video capture, and easily interchangeable instrumentation modules. The vehicle will in most applications be designed as a one time use disposable. The deployment possibilities for this concept include: deep-ocean hydrothermal vents, sub-glacial lakes, acidic or alkaline lakes, and possibly planetary ocean environments. This initial concept for MASE was designed as an Astrobiology explorer

Introduction

This concept is based on work at the Jet Propulsion Laboratory together with close collaboration with experts from the Angstrom Space Technology Centre (ÅSTC), Woods Hole Oceanographic Institution (WHOI), S-SENCE inc., Sweden, and the Southampton Oceanographic Institute (SOC), UK.

Today the search is on for the origin of life, and thus the limits on and ultimate understanding of life are being investigated on a broad front. In order to truly understand life we have to reach beyond established findings and their predictions. We have to investigate harsh places, often never visited by humans before, and perform in-situ measurements. There are very interesting sites on earth where life or biomarkers have been found in extreme environments believed for a long time to be sterile. For instance, investigations of hydrothermal vents in the deep oceans on earth have already revealed almost 500 new species previously unknown to science. Similar results have come from studies in the world's "lake" type extreme environments. Among the most interesting sites many are difficult to access. The famous Lake Vostok under the thick Antarctic ice sheet is a good example [1]. Other lakes are in volcanic subglacial environments, in brine lenses in permafrost and in similarly inaccessible locations. This concept addresses the technology to explore these remote lacustrine and marine environments and provides advanced techniques for an exploration vehicle for the liquid ocean on Europa.

The platform concept devised is a fluid compensated miniature robotic submersible vehicle (hydrobot) endowed with autonomous control and real time onboard scientific measurement and analysis for intelligent input to the autonomy system. An illustration of the concept is shown in Figure 1.

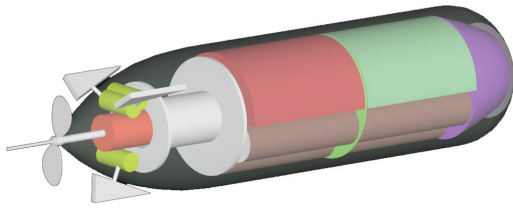


Figure 1. An illustration of the Miniature Autonomous Submersible Explorer (MASE) vehicle.

Baseline concept

A goal of the baseline design is to examine the benefits of innovative miniaturized instruments fabricated from novel MEMS technologies. This allows it to be a flexible platform with the size to fit inside other vehicles. In particular the miniature submersible concept addresses many scientific and technological interests of the astrobiology community. The small size and specific chemical instrumentation will allow for determinations of the composition of a possible sea on Europa while in the short term generating in-situ astrobiology data on extreme and previously inaccessible environments on Earth.

The miniature submersible is designed as a specific data-taking device rather than a general purpose vehicle onto which instruments can be mounted, the usual submersible implementation approach. Consequently, a change in observational task will result in a redesign.

The objectives of the concept and the following investigations for this platform can be summarized as follows:

- Provide access to subglacial and other remote and chemically (and or environmentally) challenging aquatic environments.
- Acquire images and comprehensive hydrographic and compositional data from the submersible.
- Operate and conduct a science program fully autonomously
- Enter and function with minimal and controllable contamination of the site
- Be simply deployed and cheaply shipped.

The range of the submersible will be adapted to specific explorations, but it should not be restricted by the design to less than 1 km in order to benefit the most from its survey type capabilities. In general there is no limit to the desired ultimate miniaturization (an extreme level of miniaturization would be needed for Europa),

but near term dimensions should be targeted at subglacial vehicle designs (See e.g., Figure 2, a tested Cryobot vehicle), i.e., the submersible should be less than 8 cm in diameter and less than 30 cm long [2].

This vehicle is initially designed as a disposable unit when deployed. This is done to simplify its design and because certain design decisions are affected by this requirement. Examples of some of these are:

- Must be engineered to be low cost
- Allows higher density energy storage than rechargeable batteries
- Requires no provision needed to locate and return unit
- Is less risk averse; bulk fabrication means that not everything is riding on a single expensive vehicle

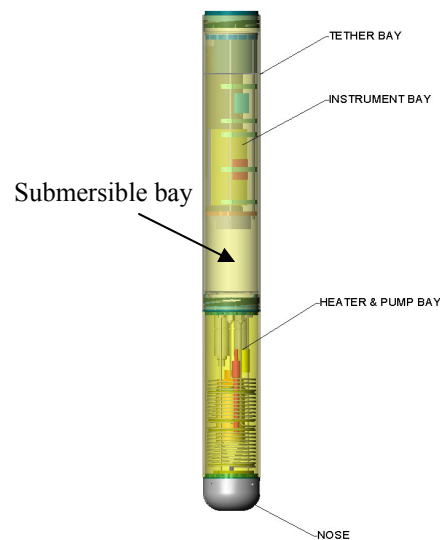


Figure 2. An illustration of a "Cryobot" vehicle developed and tested by JPL. This figure shows the internal distribution of subsystems within the vehicle.

Astrobiology science

Astrobiology is the science of life in environments other than Earth. Based on our understanding at present, astrobiology in our solar system qualifies as extremophile biology; those habitats we customarily associate with life may not exist, and we expect to have to search for life in sites that are characterized by extreme chemical and/or physical properties. As a consequence, astrobiology research involves the search for life in extreme environments on Earth, e.g. hot springs, ocean vents, acidic or basic lakes, subglacial liquid water, cave ponds, etc. Exploration of many of these sites, including subglacial lakes as noted above, involve stringent geometrical limitations in the probes

as well as challenging tolerance to pH, pE, temperature excursions, radiation, and pressure. In the case of an actual planetary deployment, e.g., to the subglacial ocean on Europa, the environment is not specifiable, and these operating geometrical constraints and environmental tolerances are essential.

The focus of the science objectives for this design exploration will be in three fields, subglacial lakes, hydrothermal vents and Alkaline or Acidic lakes.

A. Science Instruments

An important instrument is a microelectromechanical systems (MEMS) Electrochemical tongue. It is supplied by the S-SENSE Centre from Linköpings University, Sweden [37, 38, 39, 40, 41, 42].

The basic instrument set contains:

- High resolution camera
- Depth & Temperature sensors
- MEMS Electrochemical tongue, which measures
 - pH
 - Dissolved atmospheric gases
 - Ion detector
 - Conductivity (salinity) sensor
 - Growth of organisms
 - Separation of different strains of microorganisms

B. Science Scenarios

Subglacial and Ice covered lakes: Subglacial marine and lacustrine environments are amenable to simple vertical profiling using standard drilling for access and commercial water-profiling systems for chemical and physical data taking. However, other examinations of these environments, e.g. roof, wall and lake bottom characteristics and horizontal homogeneity, require a 3-dimensional observing capability that is clearly not readily available for this environment. In addition the subglacial environment may be sharply stratified with very dilute chemical constituents, i.e., delicate layering, so that an exploration system must be deployed which will disturb these layers minimally. Use of traditional submersibles is challenging as they are typically too large for drill-hole access and will disturb layers as well as low-density sediments. Subglacial site explorations have in addition a sterilization requirement that is difficult to meet with commercial submersibles.

Hydrothermal vents: Submarine hydrothermal activity, in which seawater circulates through and cools freshly formed ocean crust, plays host to unique chemosynthetic organisms and communities, some of

which may have relevance to the origins of life. When hydrothermal vents erupt they typically generate buoyant water masses that undergo turbulent mixing (hence dilution) with the ambient, stratified, water column until they reach some level of neutral buoyancy, typically 100-300m above the seafloor. The time for emplacement of such a hydrothermal plume is of the order of an hour during which time the initial fluid undergoes ~10,000-fold dilution with ambient seawater - i.e. the resultant plums represents 99.99% ordinary seawater and only ~0.01% primary vent-fluid. However, for certain chemicals (notably Mn, Fe and CH₄) the initial vent-fluid compositions are so enriched (ca. 1 million-fold) compared to background that even these extensive rapid dilution yields a strong chemical enrichment that can be exploited. The objective of exploration of the hydrothermal vent system with a MASE system is to enter and travel in the interior waterways where water temperatures are sufficiently large that most biology is not possible, but key thermophiles may thrive, e.g. temperatures above 115°C. These water ways are known to be 10-30 cm diameter at their outlet, and probably have smaller diameters down the vent. It would be scientifically interesting to explore to ambient temperatures in excess of 150°C.

Alkaline lakes: Earth possesses several examples of alkaline environments characterized by high sodium/carbonate content. Areas such as the prairie region of Alberta, Canada, the alkaline lakes in Turkey, the shallow lakes of the Russian steppes, the lakes of the southern part of the Great Plain of Hungary, the Sandhills lakes of Nebraska (McCarraher 1977) and even Mono Lake in California may be included among these (Romero et al, 1996). No studies of eukaryotic microbes living in alkaline extremes have been done. Even Mono Lake which may qualify as one of the best studied alkaline environments lacks molecular studies focusing on eukaryotes, a group often not considered in many investigations of extreme environments because they are assumed incapable of coping with physical extremes. Recent diversity studies from an acidic /heavy-metal-laden river in Spain (Amaral Zettler et al. 2002), however, reveal that a diverse range of eukaryotes is quite at home in pH extreme environments. The ability of eukaryotes to thrive in an environment may reflect the capacity of a given environment to support life. From a very limited sampling, Zettler et al. discovered that the Nebraskan alkaline lakes (pH 10.1-10.4) they sampled also support an impressive diversity of eukaryotic life. Due to limitations in the sampling regime, which this technology can support, they were unable to collect very valuable geochemical data (beyond temperature and pH) at the same time samples were taken for DNA analysis that would have greatly enhanced the study.

This is a significant limitation for microbial environmental biology, particularly in extreme settings.

Operating scenarios

A prime advantage of the new mini-sub is that it can be launched from a variety of support vehicles. A possible operating scenario is to join ongoing research programs during deployment phase to extreme environments. For instance, Southampton Oceanographic Center (SOC) in the UK have a range of deep-tow vehicles, and a long-range AUV the AUTOSUB, which can prospect for hydrothermal signatures over long length scales (10km-100km) but which are unable to stop at one location and conduct detailed seafloor searches once a “hotspot” has been identified. The ability to launch a mini-sub at such a location to fly its own mission to the seafloor over these relatively short length scales adds immeasurable value, e.g. to locate and image the life forms that inhabit such sites. An added benefit of such a deployment is that this type of exploration is a strong analogue for a future plan to study sub ice regions of Europa where a liquid ocean is thought to exist.

Submersible design

The submersible design is modular and as open as possible; where each part can easily be exchanged or customized for different applications. The design vehicle is equipped with a basic set of functions and instruments. The standard system functions are;

- Autonomous and Commanded Control
- Power Distribution and Conditioning
- Optical Fiber Communications
- Vehicle Localization and Navigation
- Health Monitoring and Hazard Avoidance

Equipment bays are provided so a number of mission specific modules can be integrated. Examples of such modules are;

- Various science instruments
- Real-time scientific analysis computational processors.
- Large data memories

The submersible vehicle design is illustrated in Figure 2 which shows the distribution of functions and the vehicle sizing of the subsystems. The vehicle is roughly 20 cm in length, and 5 cm in diameter not including the variable (1-3cm) optical fiber protection in the end.

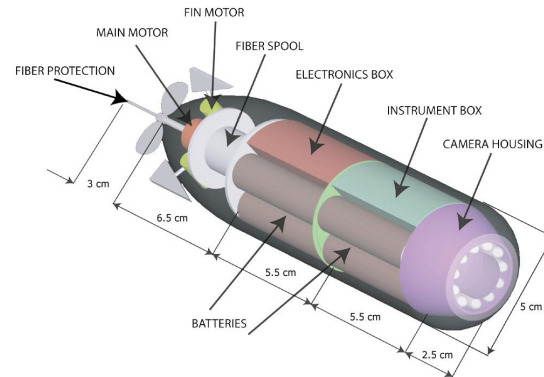


Figure 3. An illustration of the miniature submersible vehicle. This figure describes the internal distribution and sizing of the vehicle subsystems.

The instrument bay may include 2 to 6 instruments depending on the mission. MASE is designed to be self deploying or to fit inside other vehicles (i.e. a deep ocean mother ship, a Cryobot, a spacecraft, etc.). The vehicle has an onboard spool for optical fiber stowage ranging from 100s of meters to kilometers of tether. The spool will be paid out with a small motor that can compensate for some of the effects from currents pulling on the fiber. The vehicle incorporates a small Inertial Navigation System (INS) for its own localization and navigation. The development issues for advancing the MASE system technology to the level assumed here include interfacing current MEMS sensor instruments, liquid compensation of MEMS and system components, control system design and software, active optimal power usage, and real time autonomous processing of scientific data to send back results and direct the guidance system.

Subsystems

Several of the key subsystems are detailed in this section.

Data Handling and Signal Distribution

An I²C [42] bus with a distributed protocol acts as the backbone network between different modules. Commercially available Micro Controller Units from Atmel are used that have built in hardware support for the I²C bus. The ATMEL MEGA AVR 161[43] is an efficient MCU with I²C built in with both Master/Slave operations. The I²C bus is included in every module through at least one MCU or FPGA and each unit is allowed to talk to any other I²C unit on the bus [44]. Figure 4 shows an illustration of the distributed bus architecture

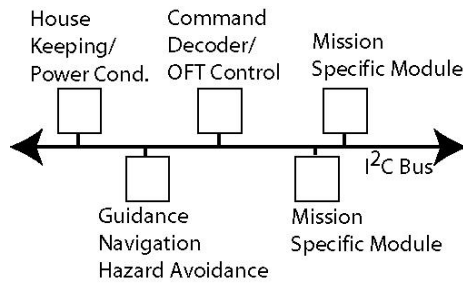


Figure 4: This figure show the distributed architecture over Philips I²C bus. Several small FPGAs/Micro Controllers are used and all are allowed to communicate with each other.

High speed peer to peer (P2P) data links are provided for intense data transfer applications, like a high resolution camera image processing. The high speed data links are subsequently connected directly to the Optical Fiber Transceiver module.

Guidance, Navigation and Hazard Avoidance

For guidance, navigation and hazard avoidance there are several well developed MEMS sensors available today and a wide range of new ones coming out [45]. The most important sensor for this application is the MEMS accelerometer, and four are included in the Guidance and Navigation module, two primary and two redundant. The accelerometers give input to the steering control loops and also detect a collision with an obstacle. Problems with parasitic capacitances that can interfere in analogue I/O signal interconnections are minimized with a correlated double sampling (CDS) technique [46].

The navigation unit can process scientific data from a selectable set of instruments, e.g. from Conductivity, Depth and Temperature (CTD) sensors. Should the mission require analysis of large data sets from special instruments, the processing capability needed is implemented in the instrument unit and the navigation inputs are fed to the navigation MCU over the I²C bus. The Guidance and Navigation module includes large FLASH storage memories that can be used to preprogram a certain mission profile or be used as a reference lookup table for scientific measurements.

Health Monitoring and House Keeping

The house keeping (HK) module is designed with a large number of A/D and D/A converters, some to be used by default for built-in sensors and monitoring, but

a large number of extra A/D and D/A channels are open for mission specific modules. Further incorporated in the house keeping module are power conditioning and distribution electronics. The HK module is set as master when the submersible is switched on and goes through a system check before releasing the I²C communication bus. If a module or function should fail the HK system has the authority to override and reset other systems. A real time clock (RTC) is also implemented in the HK module. The RTC is connected to the I²C bus and any unit can communicate with it. The RTC is primarily used to mark scientific data but it can also be used in missions that are sequenced according to a time phased profile.

Optical Fiber Transceiver / Command Decoder

The optical fiber transceiver (OFT) is a key component in the miniaturization limits. Figure 5 sketches a MEMS enabled OFT packed in a Multi-Chip Module and located inside the fiber spool to rotate together with the spool. The OFT is designed to be a self-sustained full duplex module with its own Power Conditioning Unit (PDU) and necessary FIFO buffer. Slow scientific and housekeeping data are mixed with high bandwidth image data in the communication protocol by the local micro controllers (MCU) inside the module. The OFT module uses multimode (62.5um core, 62.5 um cladding, 200um diameter) optical fiber capable of transmissions up to 155MB/s. Figure 8 illustrates a cross section of the OFT module using 5 silicon wafers plus an Interconnection Wafer Interface to a flexible cable wafer stack of a total height of 3.5 mm. The module has a circular shape with a diameter of 15 mm, and an estimated weight of 2g including the optical fiber mounting.

The OFT Module is designed to have full duplex data transfer, but the bandwidth is reduced to the submersible (upstream) in order to save energy. Upstream data is interpreted by the Command Decoder and can include commands, parameters or vehicle firmware updates. The command decoder is implemented in an FPGA and connected to the system over the common I²C bus. The downstream dataflow can be varied subject to mission requirements. Optical fibers have been used successfully at great ocean depths and provide a robust underwater communication system.

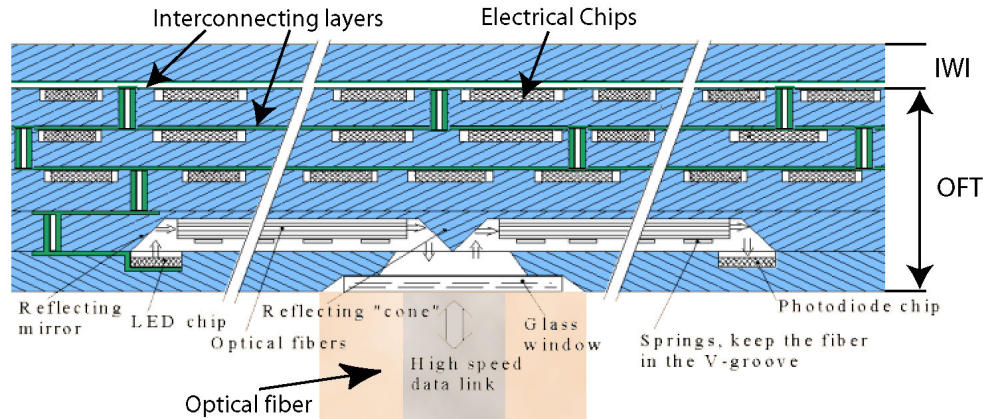


Figure 5: Optical Fiber Transceiver (OFT) Module 3D-Multi Chip Module design. The OFT designed on 5 silicon wafers and an extra Interconnection Wafer Interface (IWI) to flexible cable is added.

Power System

It is estimated that the total power storage currently available in the form of primary Li-ion batteries can be 30-40 Ah. These units can be contained using the bottom half of the vehicle. The power conditioning and distribution electronics is included in the House Keeping electronics.

Conclusions

A MEMS-based miniature submersible is very close to realization and would constitute an exploration vehicle of value to the scientific community. While a complete system and subsystem miniaturization using MEMS components is the current goal for this vehicle, there are several technological challenges to overcome. Investigations on the behavior of MEMS components under high pressure in a fluid compensated environment need to be conducted. New connectors and module designs must also be identified to minimize the size and mass. These challenges as well as traditional ones in miniaturization such as adequate energy density in storage systems and adequate torque outputs for propulsion make this endeavor an exercise in pushing the current boundaries for vehicles used in the extreme environments described.

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