A HEAVILY MINIATURIZED SUBMERSIBLE
– A TERRESTRIAL KICKOFF

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The vision of exploring extraterrestrial water findings employing a remotely operated
submersible, as proposed by JPL/NASA for the investigation of the possible ocean
underneath the frozen crust of Jupiter's moon Europa, is now taking a step further into
fulfilment. The Ångström Space Technology Centre has developed a sophisticated vehicle
concept based on microtechnology for most of the navigational systems and payload
systems. This enables a high function density, and a compact vehicle with a diameter of 50
mm and length of 200 mm, i.e. an overall size allowing the vehicle to be deployed through
a borehole like that typical for arctic drilling.

Here, the system architecture of the vehicle complying with the requirements on
manoeuvrability, operational functions, and mission objectives is presented. In short, the
vehicle in the first version will operate in deep and narrow waters, and will be equipped
with a camera, sonar imaging system, an electronic tongue for chemical sampling, and a
Conductivity-Temperature-Depth (CTD) sensor. Although the vehicle will be given certain
autonomy in later versions, the first edition will rely on remote manual guidance.
Commands for this, as well as power download, and data upload will be communicated
through an optic fibre.

The objective of this contribution is to present, for the first time, the status of the project
including, briefly, the first results from miniaturized sonar, the vehicle bus design, and the
design, realization and testing of the propulsion and attitude control systems differing in
manoeuvrability, weight/volume, redundancy and efficiency.

1   INTRODUCTION

Although the pictures taken and measurement made by spacecraft have strengthened the
theory of water existing under ice the crust of Jupiter's moon Europa, we can not verify it
unless going there. NASA/JPL has ideas of sending a robot to take samples and make
measurements on site. Their Hydrobot, for instance, is a planned future intelligent
autonomous robot for exploring this moon [1, 2]. Before going there, we have to learn how
to carry out a mission in such an alien environment, and a good place to learn is Earth.
Missions to Lake Vostock were real exercises of ice drilling toward water, and deployment
of a submersible robot for search of life form. The experience gained on Earth will help us
to succeed in a space mission.

Deeper Access Deeper Understanding (DADU) is a Swedish, MISTRA-funded project that aims to build a heavily miniaturized submersible using MicroElectroMechanical System (MEMS) technology to decrease its mass and volume, and to increase the density of the sensor systems onboard.

The primary objectives of the project are to develop, build and evaluate a miniature remote-controlled submersible serving as a multipurpose instrument platform for exploration of deep waters difficult to access. The evaluation will be made through environmental explorations on Earth, but with a space application perspective. The secondary objective is to make an inventory of the present and future environmental issues and explorations likely to benefit from this platform, and build a network for future development and exploitation of the vehicle.

Some of the top-requirements on development of the vehicle are that it should be small enough to be deployed through a borehole into thickly ice covered water, or into narrow caves. The vehicle should be capable to operate in water with control commands from ashore for several days, with intermediate hibernations for on site battery charging. The vehicle should not leave any traces affecting the environment of the visited waters.

This paper will mainly describe the concept of the vehicle, its system architecture and its specific manoeuvrability for operation on the aimed sites. Some highlight on the payloads will also be briefly presented.

2   THE SUBMERSIBLE VEHICLE

It is not the intention here to build a vehicle competitive to those earlier deployed in deep seas using conventional technologies, both large and small submersibles, but to build a much smaller submersible, yet extensively instrumented, with a niched range of applications. A number of vehicles with varying size, operation depth and autonomy, such as DEPTHX, Bluefin-9, SeaBlue, SeaSwarm, GAVIA, Iver2, AUV and ROV from Necton Research, etc. [3], have been studied. A common feature is that they employ, to a large extent, conventional technique and components off the shelf (COTS) for miniaturization. The use of MEMS technology has not been specifically stated for these vehicles. It is, however, most likely that they use commercial MEMS systems to a limited extent. For instance, some of them use accelerometers from the car industry. In DADU, MEMS is a means to miniaturize a large number of systems, especially the payloads. MEMS technologies also provide sensors and other instruments with better performance. By using MEMS, a major reduction of the vehicle's total weight is possible, which makes it easier to keeping its mass density close to that of water. The hull and some other mechanical parts, for instance those employed in propulsion and attitude control, are not MEMS-based, however.

2.1 System Architecture

The vehicle is divided into five areas, with regard to system architecture view: power, microcontroller unit (MCU), propulsion, sensing (or payloads), and communication, Fig.1.

The power system consists of rechargeable battery packs, which supply power to all units during active operation. During hibernation, only a part of the microcontrol unit (MCU) is alert.

The MCU is the brain of the vehicle. Almost all signals travelling inside the vehicle will, at some point, reach this unit. It performs basic signal processing, controls peripheral units, performs AD-conversions, and stores obtained measurement data in its memory. When batteries are running low, it can put itself and the rest of the vehicle in hibernation mode implying a power consumption in the microwatt range to recharge the batteries through the fibre optic interface.

The propulsion system consists of eight thrusters that enable the vehicle to move freely with five degrees of freedom. (Rolling is absent.). Stabilisation and attitude control are taken care of by the propulsion system.

The sensing system covers standard functions of a submersible vehicle, and will be prepared for integration of mission specific payloads. The sensors under development for this vehicle prototype are: video camera, sonar, CTD, electronic tongue, and sensor for heading and navigation.

The communication system is optical. It passes all raw data, and control signals between the vehicle and the control station ashore through an optic fibre. This fibre is also intended for sending light energy for charging the batteries.
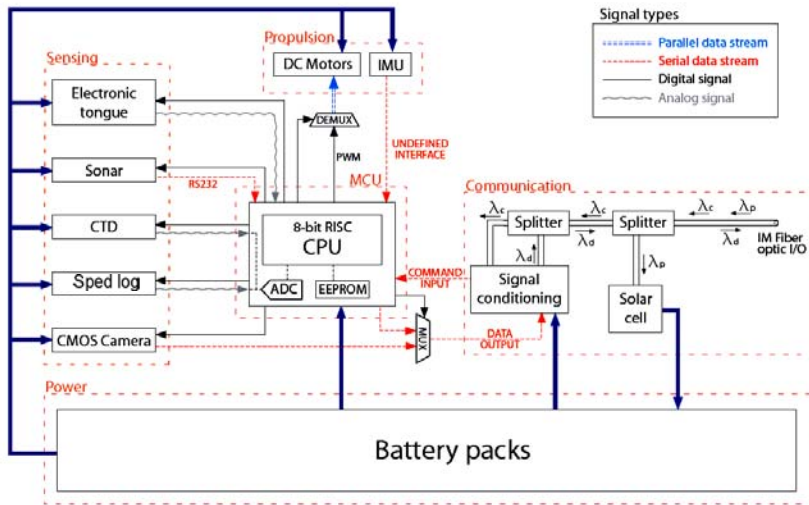

Fig. 1: System architecture of the DADU

2.2 Design Concept

From a survey study on mobile deep ice drilling business, a cylindrical envelope with a diameter of 50 mm and a length of about 200 mm for the vehicle was found suitable. After a design concept generation and evaluation phase, the final hull and propulsion concept, Fig. 2, has been chosen. This concept attempts to maximize the vehicle's manoeuvrability in narrow waters. The manoeuvres include pitch and yaw on spot, vertical and horizontal translation, and back and forth movement, with a certain redundancy. These are enabled by two attitude control units with vertical and horizontal thrusters in front and rear, and a main locomotion unit at the stern. As seen in Fig. 2, failure of one motor for pitch and yaw in the attitude control units does not take away these manoeuvres, but then the vehicle requires a certain radius for turning. Even if both motors for pitch or yaw in the attitude control units stop, the vehicle can still passable do the manoeuvres by using appropriate pairs of the motors in the main locomotion unit at the stern. The translation movement then cannot be performed, however. With all thrusters in good health, the vehicle can propel, hover, translate, and even do a so called devil's eye, just like a helicopter can do, without rudders and stabilizers.

Due to the high outer pressure on the vehicle, it is desirable to make the hull from as few cylindrical and domed pieces as possible. Every constituent piece, regardless of it belonging to the hull or the interior, will generate interfaces, and thus requires extra material adding dead-weight. For the vehicle prototype, the hull is divided in three pieces: bow, corpus, and stern. They are all monolithic, including all guiders, fixtures, and supports

Fig. 2: Design of vehicle.

for the subsystems inside. Also here, a monolithic concept is chosen not only to avoid interfaces and connectors, but most importantly, to gain a high structural strength. This structural design requires casting, or solid freeform technique that deposits material where it is needed, to be manufactured. This prototype employs an inexpensive rapid prototyping method; based on fused deposition modelling (FDM) using an ABS-plus plastic to build a light weighted hull.

Leakage is an important issue for a submersible vehicle. All lead-through in the hull, especially for rotating motor shafts, will imply a leak risk and thus cost for mitigation. Use of submersible electric motors is a way to mitigate the problem. Another method is to compensate the outer high pressure by filling the voids of vehicle with a more or less incompressible liquid. This should be a promising method although one has to regard the overall density that needs to be close to that of water, as well as the fact that not all subsystems are pressure tolerant.

2.3 Camera

A CMOS video camera is planned to be placed behind a port glass at the foremost position of the bow. When activated, the live video signal will sent back ashore through the optic fibre. A white light diode ring will be positioned slightly behind and around the port glass. Since small cameras with high resolution and fair sensitivity are available on the market, the vehicle prototype can use a commercial mini camera, of either an analogue with ADC or digital type. The camera chosen for this design concept is a PC-53X5 from SuperCircuits.

2.4 Sonar

A side scanning sonar will be used to obtain images of the vehicle's surroundings in darkness. The frequency is chosen so that the sonar can image the surroundings up to 30 metres. The prototype will be equipped with two parallel sonar elements integrated in the corpus part of the hull, facing down with an angle of 90° in between. This configuration enables the vehicle to see the bottom of its environment. If four sonar elements are positioned around the hull with 90° angle increments in between, they in pair should be able to scan an image of the bottom, top and sides, which are useful for navigation. It is also possible that the sonar system can be used as an emergency beacon in the case of losing contact with the control station ashore, caused by optic fibre break or other failure of the communication system in general.

2.5 CTD and Electronic Tongue

For characterization of the water surroundings, a device for measuring of Conductivity, Temperature and Depth (CTD) is anticipated. It is either a dedicated MEMS system or a

combination of the electronic tongue, a temperature sensor, and a pressure sensor. Whereas the temperature sensor is trivial in all respect the other are challenging. The pressure sensor must have a good resolution along the 1 to 1000 m vertical range of the vehicle's operation depth, and also respond quickly. As for the electronic tongue, much has already reached significant maturity [4,5], but issues on signal processing, and electronic integration remain.

2.6   Speed Log

For registration of speed and travel distance the vehicle will be equipped with a MEMS-based array of speed logs. This device is being development and is planned to be mounted on the surface of the hull.

2.7   Optic Fibre Communication

Communication between the vehicle and control station ashore is carried out though an optic fibre. The vehicle trails a 250 µm thick optic fibre for in- and outgoing signals. By using an optical splitter, the signals can simultaneously be sent at different wavelengths. Incoming signals, typically control signals, are converted to a serial digital data stream and passed to the MCU. Outgoing signals are typically measurement data and the raw camera output. Finally, a third wavelength is used to recharge the batteries when the vehicle is in hibernation.

2.8   Heading Sensor

An Inertial Measurement Unit (IMU), which is a three axial system consisting a MEMS-based gyroscope and an accelerometer, will be used to help the vehicle to keep track of its own. This system will be developed in collaboration with an extern company that specializes in MEMS. An MEMS-based magnetometer for 3D-measurement of magnetic field under development is also anticipated as an alternative or complementary heading sensor to the IMU.

3   STATUS OF THE PROJECT AND FIRST RESULTS

The vehicle is built and being tested in October 2008. The locomotion and attitude control will be extensively tested. For this purpose, a commercial radio control system is used to send the control signal to the vehicle in water. The vertical and horizontal translation movement, and pitch and yaw manoeuvres using the attitude control units are being examined separately and in combination. The same procedure will also be done for the manoeuvres performed by means of the thrusters in the main locomotion unit.

The first sonar element (the size of a matchstick) was developed using crystalline piezoceramic material and conventional processing techniques, Fig. 3. The electronic system and the software are tailored for this element, and developed in collaboration with

the company Deep Vision. The sonar system will not be integrated into the vehicle until the vehicle manoeuvrability has been fully tested. Fig. 4 shows an image acquired when testing it from a wooden bridge. The bottom right window of the picture displays the piles of the bridge and stones at the river bottom with the horizontal axis representing distance/depth, the vertical axis the travelling of the vehicle (here translation of the sonar element), and the colour intensity the strength of the echo.

The MCU with ADC is developed and programmed. It employs an Atmel microprocessor and other electronic ICs. So far, only codes for manoeuvres and actuation of light, camera, and sonar are written and tested. The MCU processes the control signals from receiver onboard of the vehicle and activates the thrusters, light, camera, and sonar. For the time being, the sonar and the camera are not yet integrated into the vehicle, however. Adding codes into the MCU for other functions will be made concurrently with integration of the subsystems. Miniaturization of the MCU using naked microprocessor and ICs by means of MEMS is fully possible, and it is intended for a further phase of the project.

The optic communication system is till under development. Some tests on the fibre interface have been performed on optical bench. (That is why all manoeuvres and actuation are controlled via the radio control system). An optoelectronic system for gigahertz communication has been developed and tested successfully.

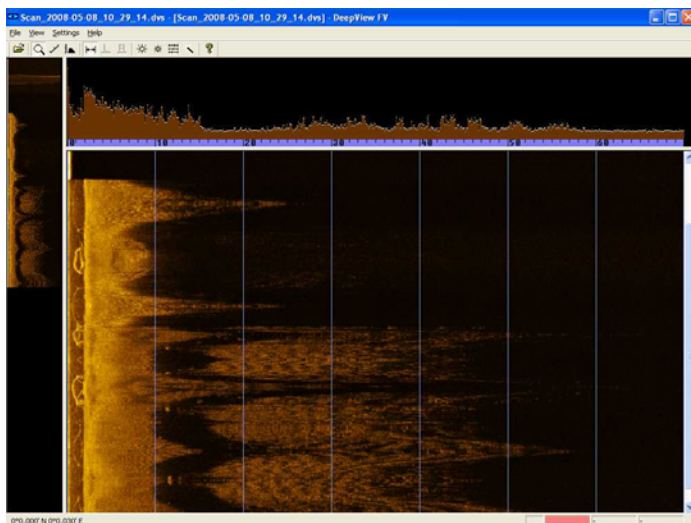Fig. 3: First microsonar element developed at ÅSTC.

Fig. 4: Computer screen dump from a test of sonar sensor.

4   DISCUSSION

The project includes development of a number of subsystems and components. The camera, motors and propellers, and batteries are COTS. All other subsystem and sensor are under development to comply with the MEMS-based miniaturization concept. Most of them are developed in parallel, but the integration into the vehicle has to be made in a certain order. By doing so, the subsystems can be tested, improved and verified separately. Many of them can simply not be repeatedly mounted in and out without risk for damage or deterioration of function and structural tolerance.

The vehicle itself, regarding hull, power, and propulsion, is a miniaturized mechanical system using conventional technique. The miniaturized vehicle has to deal with water environments that exert certain friction and drag, and it has to move and manoeuvre with a certain velocity, with a fibre optic trail. Here, the prototype of plastic material is used to verify the design concept, but once this is done, the same, although revised, CAD files will be used for manufacturing of the vehicle a material with high pressure resistance.

The propulsion system in this prototype uses miniaturized electric motors and propellers, which are not hydrodynamically optimized and not classified as pressure proof. Alternative propulsion systems are to be developed. In general, these should not entail any lead-through in the hull. This will be challenging for the reason, among the other, of the requirement that states no contaminating traces should be left in the visited waters.

For the attitude control units, high resolution is more important than the high thrust, while both high resolution and high thrust is important for the main locomotive unit. Since the control pulses to the motors are digitalized, the resolution is limited by both the number of bits of the electronic system, and by the characteristic of the motors.

Communication using optic fibre implies that a spool for storing a long and thin fibre, with the belonging mechanism for releasing and reeling the fibre, has to be used, and to be preferably placed in the stern of the vehicle. Sophisticated control on strain of fibre will be required, not only when deployment of and homing the vehicle, but also when a wave of water hits the vehicle or the fibre.

5   CONCLUSION

So far, the results from tests of vehicle design, its manoeuvrability, sonar, and MCU are promising. Their performance still needs to be improved, however. Development of new MEMS-based sensors is the most time consuming, while other systems employing conventional techniques and COTS, such as mechanical and electronic, usually get good results in fairly short time. The project is still far from its final goal that is to build a heavily miniaturized multipurpose instrument platform for exploration of deep waters difficult to access. To reach that goal, not only the systems brought up here have to be completed, but many other instruments, and algorithms for navigation and guidance, obstacle avoiding, homing and docking, fault management, etc, have to be developed.

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