Design of an Autonomous Under-Ice Exploration System

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I. Introduction

Exploration of under-ice environments has gained importance in the last decades. Reasons for this range from political (extension of the exclusive economic zone) to scientific (researching climate change, marine biology). The work in this paper had yet another key motivation: exploration of Jupiter's ice-moon Europa. Planetologists predict an ocean of liquid water below an ice shield with 3-15 kilometers thickness. This huge ocean (estimated depth: 100 kilometers) is one of the most likely places for extraterrestrial live in our solar system, and thus of high interest. The project "Europa-Explorer" is a pilot survey for future missions to Jupiter's moon Europa. Its scope is the design of a fully integrated autonomous under-ice exploration system, which will be prototypically built and tested in arctic environments on earth. This paper will describe this design process and the robotic system which will be build in the course of 2013-2014. Besides the application on extraterrestrial missions such a system could be highly interesting for research on earth, especially, since the first test prototype will be build for a terrestrial environment.

II. Mission Requirements

The target Europa comes with some special mission requirements. Before going into more detail on these requirements the mission outline should be given:

- Penetration of the ice shield
- Ejection of an exploration-AUV
- AUV sinks to ocean floor
- Autonomous exploration of the ocean floor and acquisition of measurement data
- Return to the point of entry
- Docking with the ice drill
- Re-charging and then repetition of exploration

The aspect of reaching Europa and landing on it are outside the scope of the project and this work. The mission scenario is also depicted in figure 1.

In this pilot survey a few alterations on this missions are necessary: Obviously the huge vertical distances on Europa are not directly tested on earth, the same goes for details such as radiation, environmental conditions and degree of autonomy. This results in a modified terrestial setup with some modifications: The prototype system will only be constructed to withstand depths of 100 meters, and should be able to drill through 10 meters of ice. The under-ice navigation part remains more or less the same. As additional difficulty for the terrestrial mission a re-integration into the ice drill and return to the surface are necessary, since the prototype exploration AUV should be re-usable (in contrast to a real mission to Europa, where the vehicle will remain below the surface after the end of the mission). The following sections will describe the main parts of the prototype system in further detail.

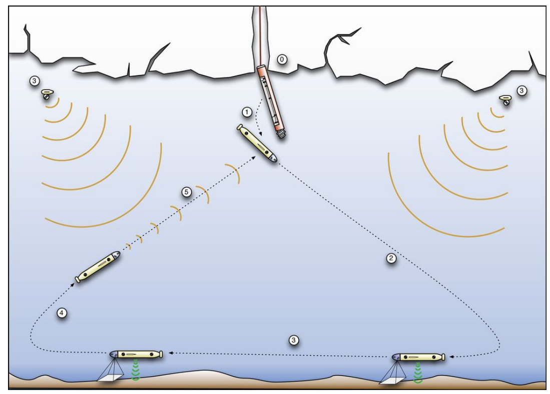

Fig. 1. Schematic overview of a possible mission scenario. 0) ice-drill penetrated the ice-shield. 1) AUV has been released from the payload compartment. 2) AUV descends to ocean floor. 3) exploration using cameras/sonar and internal sensors. 4) ascend to the ice/water boundary. 5) return to ice-drill (using autonomous localization buoys) and docking for energy/data exchange.

III. Ice Drill

The first requirements is to deploy the AUV into the ocean. Typically under-ice exploration on earth is either done by drilling a hole for the AUV using manually operated drilling equipment [1] or by entering from the border of the ice at the open ocean [2]. Since both scenarios will not be possible, the exploration AUV will need to be transported through the ice by a robotic ice-drill. Autonomous ice-drilling has been shown before ("IceMole" by FH Aachen [3], "Cryobot" by NASA [4]), but never with a complete AUV as payload. This holds a lot of additional challenges (e.g. energy, sensor deployment, in-ice navigation) which impacts the design process. Since the

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robotic system designed for this purpose is more than a simple autonomous ice-drill, it was named “ice shuttle”.

Main tasks of the ice shuttle will be:

- Transfer of the AUV trough the ice
- Guarantee a defined and solid position at the barrier of the ice (final position)
- Deploy and launch the AUV
- Provide additional navigation systems for the AUV
- Provide a docking interface for the AUV
- Recover the AUV into the transportation bay (on earth)
- Compact integrated system (energy use, descend)
- Deployment and reassembly (compact system)

Correlated to the size of the AUV (185 mm in diameter), the shuttle will mainly consist of a tubular structure with a diameter of 246 mm and of an overall length of about 5 to 6 meters.

The shuttle will be divided in segments as followed:

- Melt module
- Sensor module
- Transport module (AUV)
- Docking and deployment storage
- Ice anchor/ Umbilical
- Umbilical/ Winch (surface)

Since the shuttle is supposed to be recovered to the surface, a storage container for cable payout, which is in general part of a mole will be economized. Harbored in the sensor module the shuttle will carry additional devices to support the navigation algorithm of the AUV: a reverse USBL (Ultra Short Base Line), an acoustic beacon and a CTD-watersampler (Conductivity Temperature Depth).

To transfer the AUV through the ice the shuttle will be designed as a mole that melts through the ice. The presented concept will use electric energy from an umbilical, to melt through the ice by use of electric heating-cartridges. The available power for the melt head will be limited to 3.6 kW provided from the surface, leading to an estimated velocity through the ice of about 0.7 m/s. Using a mechanically aided thermal drilling mechanism is also considered and will be evaluate along the project, while it’s not the studies topic. The goal is to study the shuttle’s capability as a transfer, launch and recovery system, as part of a overall complete mission-demonstration (exploring Jupiter’s moon Europa). Anyway, using a combined drilling mechanism will be necessary, because of dust particles that can be concentrated by the melt water in front of the shuttle, as well as layers of dust or crusts of salt. Using only thermal energy as a drilling mechanism, the shuttle will not be able to overcome these obstacles. It will cause a full stop of the shuttle’s descending and lead to a premature end of the whole science mission. A combined mechanism can also be capable to optimize the efficiency of the thermal drill. For a real mission this electrically powered thermal system is not feasible. Since RTGs (Radio Thermoelectric Generator) are the energy source of choice for deep space missions [5], it is reasonable to use their thermal energy directly, instead of converting it to electricity and afterwards back to heat.

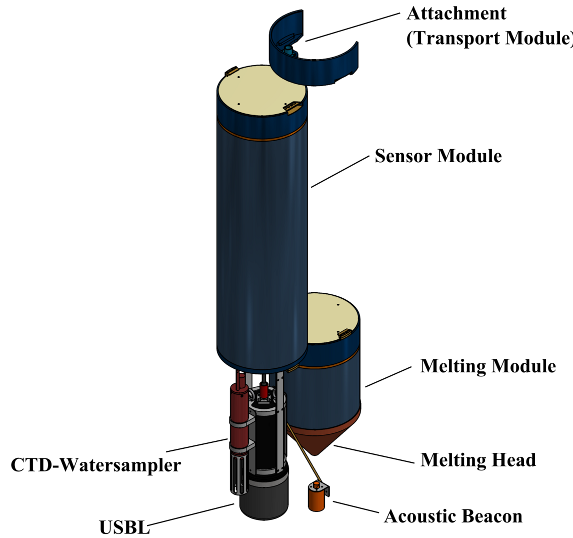

Fig. 2. Unfolding lower part of the ice shuttle

After descending through the ice the shuttle will break through the ice-barrier into the ocean. While in a real scenario the shuttle would not be equipped with an umbilical, a system, function as an anchor will be mounted to the rear of the shuttle. Thus the shuttle will be able to keep its position, while partly stuck in the ice as a base.

To launch the AUV the ice shuttle has to unfold. Because of the terrestrial experiments, a re-surfacing and therefore re-folding is necessary as well. Also the additional navigation sensors (supporting the AUV) have to be deployed. Here a free emission corridor for the acoustic systems has to be guaranteed. Taking these requirements in account, the deployment mechanism was designed, so that each of these two modules can be rotate along side within the cross-section, to open up free space along the main axis of the shuttle’s tubular structure. To do so the melt module as well as the sensor module are mounted with an ex-centric shaft. Varying the modules position, it either provides free space below the transport module to launch the AUV or clears the area below the sensor module to deploy the additional navigation systems (see figure 2).

To unfold the ice shuttle and launch the AUV, it has to be taken in account, that the barrier between ice-sheet and ocean can be heavily structured.This specially is an issue with a very long vehicle to be ejected.That’s why the AUV is planed to be deployed mainly along the main axis of the shuttle and only at a lower point of the transport module horizontally. Thus the system should be able to bridge smaller unevenness, while still providing a solid basis in the ice. Being transferred to a horizontal position by the aid of the AUV’s buoyancy system, the vehicle will un-dock and start its mission.

After the successful return to the ice shuttle the AUV needs to dock in order to exchange energy and data on the one hand, and in order to be re-integrated into the ice-shuttle for re-surfacing in the terrestrial scenario. While autonomous docking of AUVs has been shown before (e.g. [6]), the integration of such a system into the space-confined under-ice exploration system has its own challenges.

Finally the shuttle will refold, the anchor will release and the system will be recovered to the surface, dragging the umbilical upwards by use of a winch.

IV. Navigation

One of the key questions for any mission under-ice is navigation. Without a readily available emergency strategy such as surfacing and subsequent manual recovery, the navigation system for under-ice deployments simply needs to work for the mission to be successful. As a consequence the navigation system was designed to be as robust and redundant as possible. It will use a combination of acoustic, visual and inertial navigation modalities.

Inertial modalities include accelerometers and fiber optic gyroscopes, which are independent of external measurements but experience signal drift. They will be used for attitude control on the vehicle.

Visual modalities include a short-range docking camera for fine navigation during docking as well as three localization cameras. The latter are used in a bottom-lock mode after the sea-floor is reached for locally consistent ground-based navigation (more details on this visual SLAM approach see [7]).

Acoustic modalities include a dual-head 1.2 MHz DVL (ice- and ground-locking) for dead-reckoning (together with the IMU and the pressure sensor), a reverse-USBL for mid-range navigation near the ice-drill as well as a modified OWTT (one-way-travel-time) beacon acoustic localization system for long-range navigation. A reverse-USBL system is used in order to avoid having to carry the larger USBL sensor on the vehicle itself. The USBL system consists of the USBL sensor itself as well as a modem. The modem part is aboud 1/3 smaller, since it only requires one transducer. In reverse-USBL mode the vehicle sends a ping wit the modem, which is received by the USBL sensor (located at the ice-drill). Using its three transducers a range and bearing can be computed, which is then transmitted back to the vehicle using the available communication channel.

The OWTT system basically is a combination of stereo-hydrophone single-beacon localization with a self-deploying LBL setup. Once the ice-drill has successfully penetrated the ice-shield, a number n ¿ 3 of small autonomous beacons are ejected from the drill. Using their own propulsion system they spread randomly below the ice, and anchor themselves into the ice. This will probably in an un-coordinated manner in order to keep these systems as simple as possible. After having fixed below the ice, they listen for an activating ping. This activating ping is sent by the ice-drill itself, equipped with an acoustic transducer. Once a beacon receives the ping, it relays it on a fixed frequency. The AUV then receives n + 1 ping signals on different frequencies with each of its two hydrophones. When the position of the beacons is known and the clock of the AUV and the ice-drill are synchronized, this way a hyperbolic triangulation is possible and thus a localization relative to the ice-drill. It has been shown by Eustice et.al [8] [9] that the synchronization of two system's clocks for missions of reasonable length is possible. A re-synchronization would be necessary at each docking event between AUV and ice-drill. In order to find out the position of the beacons relative to the ice-drill, a survey has to be made after their deployment using the AUV. While the AUV is navigating in USBL-mode (knowing its position relative to the ice-drill) it uses its stereo-hydrophones at a number of measurement points around the ice drill to gather range information to the individual buoys. These raw ranges can be used to compute a localization distribution of the buoys which should be constant during the mission. The main advantage of this type of OWTT-LBL-system is its better scalability for large ranges (as opposed to a USBL system). With carefully selected distance between the buoys and the ice-drill (in the range of 1 and 1/10 of maximum vertical distance between AUV and ice-drill) the only limiting factor for this type of localization system is acoustic power available for sending ping signals large distances.

The sensors integrated into the vehicle are summed in table I.

V. Autonomy and fault detection

For the mission to be a success additionally to the navigation system also the behavior of the system needs to be reliable. When a problem occurs that may hinder or prevent the AUV from going back to the docking station, it must decide on it's own how to handle this without the possibility of human intervention. This is a difference to mission on mars for example where there is the possibility for humans to intervene at least via radio communication when a problem occurs. Under the ice of Europa this would only be possible if the AUV is physically connected to the ice drill docking station. Therefor the AUV must at least find a way to get back to the docking station to upload the already collected data that would otherwise be lost and ask a human for help. It would be even better of course to find a way to complete the current mission as far as possible. This requires a constant monitoring of system states, actuator commands and sensor values to detect anomalies or faults in the first place. The handling of the detected problem can then be done depending of the kind of problem either with predefined solutions (e.g. using other sensors to compensate for a faulty one) or using learning algorithms. The latter is for example necessary when thruster anomalies are detected to relearn the motion model.

VI. Exploration AUV

Regarding the AUV the problem is the specific necessity of a vehicle with small diameter (it needs to fit into the payload section of the ice-drill) with highly-specialized sensors for the exploration under ice - which in this combination are not available on the market, since typically under-ice-exploration AUVs are significantly bigger. AUV and ice-drill will have to be designed along-side in order to make the AUV fit the

TABLE I
LIST OF SENSORS/INSTRUMENTS OF THE EXPLORATION-AUV.

Instrument	**Property**	**Rate**	**Precision**	**Range**
KVH 1750 IMU (Gyroscopes)	Attitude (R/P/Y)	1000 Hz	0.8 ° / hr	360 °
KVH 1750 IMU (Accelerometers)	Acceleration (X/Y/Z)	1000 Hz	0.135 mg/$\sqrt{Hz}$	±10 g max
Paroscientific 6000-200 Pressure Sensor	Depth	0.02 - 449 Hz	0.01% RMS	0-137 m
Rowe Dual-Head 1.2 kHz DVL	speed over ground	10 Hz	±0.002 m/s	0.2-50 m
Micron DST Scanning Sonar	Distance	0.5 Hz[1]	-	2-75 m
2 Reson TC4013 Hydrophones	Pinger Signal	analogue	-211 dB	1 Hz - 170 kHz
Evologics S2CR48 R-USBL	Position/Telemetry	31.2 kbit/s	0.01m / 0.1 °	2 km
2 Bowtech LED3200 Underwater	Illumination	22 kHz PWM	255 steps dimmable	-
2 Prosilica GB1380C GigE-Cameras	Stereo Image	0-30 FPS	HD (1360x1024)	-
1 Prosilica GC1380C GigE-Cameras	Obstacle Avoidance	0-30 FPS	HD (1360x1024)	-
1 Prosilica GE2040C GigE-Cameras	Hi-Res-Image	0-15 FPS	Trans-HD (2040x2040)	-

payload-section of the ice-drill. The current design drawing of the vehicle is shown in figure 3.

The overall design path selected for this vehicle was a number of individually pressurized components integrated into a support structure and covered with a hydrodynamic hull. This typical design approach has a number of advantages for a vehicle with small diameter and long length: a monolithic pressure hull housing all components (e.g. as used in this vehicle's predecessor "Dagon" [10]) would result in a heavier vehicle. The open-frame approach allows usage of readily-pressure housed components (e.g. thrusters) and improves versatility when changes might be necessary in the future. In the design used for this vehicle the support structure and the hydrodynamic hull have been combined to save even more space and weight: the lower half of the hull will be manufactured from fibre-reinforced composite able to hold all components together, while the upper half only provides vehicle shape. One of the downsides of this approach is the increased number of underwater connectors necessary, since all components need to be wired together.

In order to integrate the sensors into the limited space within the AUV hull and at the same time enable the functionality of all sensors special modifications to the typical design are necessary. For example the vision systems and the DVL require openings and transparent covers in the hull structure. The stereo hydrophone, the USBL and the antenna for terrestrial communication need to be equipped with a deployment and retraction mechanism. This is necessary since the acoustic sensor systems need some stand-off distance from the main vehicle structure to operate optimally. Since the AUV needs to fit into the payload section of the ice-drill, a deployment- and retraction mechanism is necessary in order to retract the sensors during transportation. Due to the expected harsh environment the deployment/retraction mechanism is hydraulically operated and pressure compensated.

The AUV consists of the following main components:

- Main Thruster with Steering System
  The main thruster is used for active propulsion. It can be tilted and yawed for smooth steering.
- Dive Cells
  The two dive cells provide the vehicle with the ability to change both its net buoyancy and its balance in order to enable glider propulsion.
- Sensor Deployment System
  The sensor deployment system extends and retracts the acoustic sensors which require some stand-off from the main hull.
- Bow Thrusters
  The two bow thrusters enable the vehicle to execute sharp turns as well as to move sideways (e.g. for docking).
- USBL
  The USBL is used for mid-range navigation.
- Main Compartment
  The main pressure compartment houses the batteries as well as the PC systems, internal sensors (IMU, pressure) and data aquisition components.
- Stereo Camera
  The stereo camera observes the sea-floor, and yields low-baseline data.
- HQ Camera
  The HQ-camera has two roles: together with the stereo cameras it creates a trinocular vision system for navigation (see section IV) at the same time it provides high-resolution images as payload data.
- DVL
  The DVL is the main sensor for the dead-reckoning navigation system.
- Obstacle-Avoidance Camera
  The OA-Camera observes the are in front of the AUV and is used to detect and avoid obstacles in the main movement direction.
- Obstacle-Avoidance Sonar
  The OA-Sonar has the same task as the OA-Camera.

As an example for one of the individual pressure compartments the stereo camera housing is shown in figure VI. Due to the limited dimensions of the container of 230x 170x 80mm and a desired stereo base-line of 100mm ultra-compact single-board OEM cameras by Prosillica are used.

Another design constraint as preparation for a real mission to Europa is a redundant propulsion system. An ocean of 100 km depth is expected to exist on Europa and therefore much too deep for conventional, actively diving AUV exploration. In order to be able to travel this large vertical distance, but at the same time being agile and able to do ground-relative

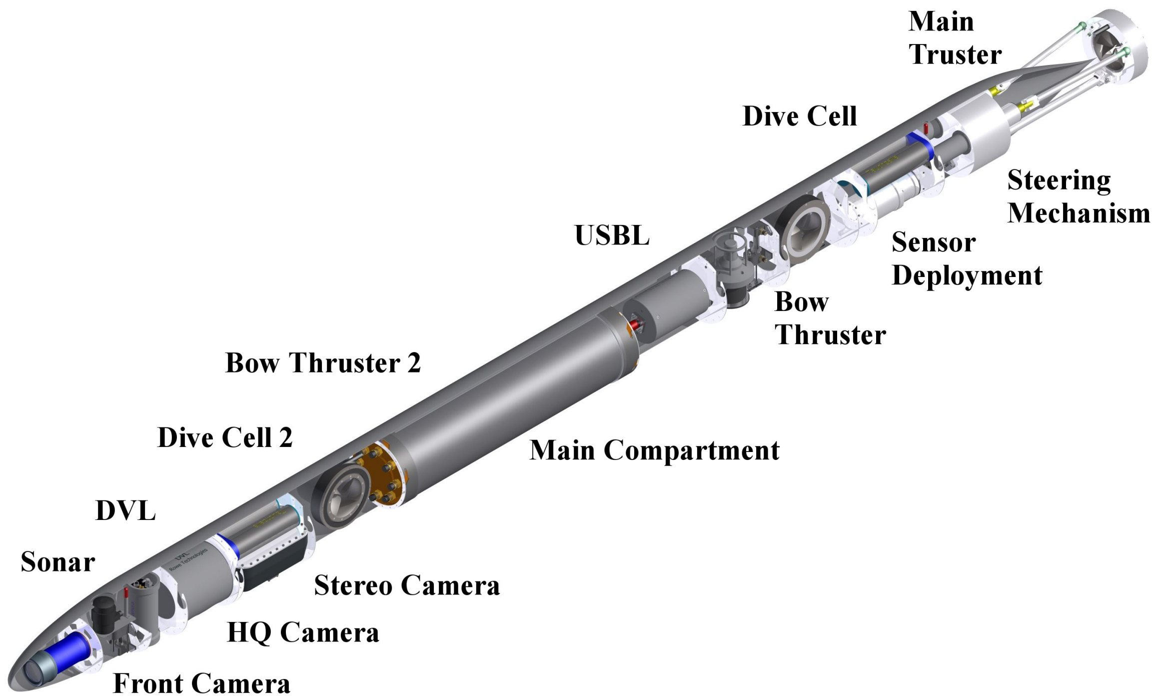

Fig. 3. 3D Drawing of the exploration AUV with sectional hull view .

navigation, a hybrid propulsion system was employed: besides the main propeller, it will consist of two variable buoyancy cells (similar to an underwater glider system). This allows changes to the overall buoyancy, enabling the AUV to traverse large vertical distances without continuous energy demands. For direction control especially while docking or exploring the ground two bow thrusters are implemented inside the AUV hull.

The main shaft-less ring thruster is supported by a retaining rod and controlled with two push rods. This system design, shown in figure VI enables a small size support structure and a precise control. The retaining rod guarantees to keep the center of the thruster in a fix position with respect to the AUV. While it is lengthwise actuated, the design allows to adjust the distance between main thruster and the rear of the AUV hull, to optimize the gliding or propulsion efficiency.

The preliminary electro-mechanical specification of the exploration AUV are:

- Length/ diameter 3500mm/ 185mm
- Estimated weight 60kg
- Lithium ion batteries 48V / 36 Ah
- Two shaft-less bow thrusters 60N
- Shaft-less main thruster 60/120N
- Two buoyancy cells

A. *Hydrodynamic Shape*

In order to allow the vehicle to utilize a hybrid propulsion system as described above, it is important for the vehicle to have a benign hydrodynamic shape. To this end the open-frame structure is encased with a hydrodynamic hull. The main

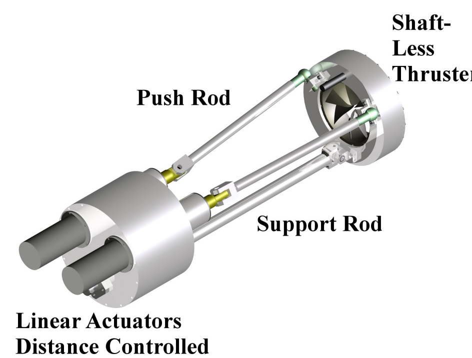

Fig. 4. Main thruster with steering mechanism.

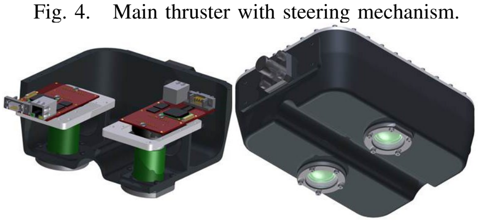

Fig. 5. Stereo camera as example of customized pressure housing.

task of this hull is to allow stable gliding as well as actively propulsed flight. As a secondary aim, it minimizes the required propulsion energy in order to prolong mission cycles. This results in an optimization of flow resistance during locomotion.

For this task a bio-inspired approach was selected: in nature a number of different body shapes can be found, which occasionally are designed for energy efficient locomotion. For instance, tunas are known to swim great distances with high velocity for foraging in a very energy efficient way occasionally due to their body shape [11] [12] [13]. To define the geometry of a tuna body shape, it is appropriate as described from Hertel [14] to use the definition of a NACA-Profile (National Advisory Committee for Aeronautics).This profile provided the basis of the front and rear shape optimization of the AUVs hydrodynamic hull, while the main part of the body remains a cylinder. This deviation from the optimal tunas shape is a result from the demand for small diameter. Additionally to this basic shape attention was required to optimize adverse hydrodynamic effects of the deployed sensors and the rear thruster, since in glider mode the vehicle is sensitive to turbulences.

VII. Conclusion and Future Work

The work in this paper is only the first stage in the development, construction and testing of the complete autonomous drilling/exploration system which is developed in the Europa Explorer project. The next steps in the process are the integration of the complete prototype system and the subsequent testing in environments of increasing complexity (test basin, lake, ocean). In two years time the final experiments are to be executed in an arctic environment.

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