The TRIPLE-nanoAUV: An Autonomous Underwater Vehicle to Explore the Oceans of Icy Moons*

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Introduction: The icy moons Europa and Enceladus represent two of the most promising candidates for the search for extraterrestrial biosignatures [4]. Scientists suspect large oceans with conditions of habitability under their ice shells. They are expected to have a thickness of several to dozens of kilometers [1]. To reach the ocean beneath, an exploration system must penetrate this massive ice shell to search for biosignatures possible. Such an exploration system must implement a surface station, a melting probe (cryorobot), and an autonomous underwater vehicle (AUV).
A range of under-ice AUV development activities are underway like the *Icefin* (NASA RISE UP program) of GeorgiaTech [5], the *DEPTHX*, *ENDURANCE*, *ARTEMIS*, and *SUNFISH* systems (NASA ASTEP SIMPLE program) of Stone Aerospace [6], and the *DeepLeng* (DLR EurEx program) of the German Research Center for Artificial Intelligence [3].
The limitation of all these AUVs is their size and weight, which does not qualify them as a payload for future space missions, and/or the absence of the combination with a melting probe capable of penetrating several kilometers of ice. Before any of these AUVs can be deployed into the water column, vertical access shafts through the ice need to be melted or drilled.

The TRIPLE System: In September 2020, the TRIPLE-nanoAUV project started to develop an exploration system that fills the previously identified gap [7].
The TRIPLE exploration system consists of three main elements, the *IceCraft* melting probe, the miniaturized exploration vehicle *nanoAUV*, and the *AstroBioLab (ABL)*. *IceCraft-2*, the longer successor of *IceCraft-1*, should penetrate the ice shell from the *Surface Station* and anchor itself at the ice-water boundary.
The smaller *IceCraft-1* melting probe was tested[1] in spring 2023 [2] at Neumayer III Station (Antarctica). The melting probe contains the *Launch and Recovery System (LRS)* with the *nanoAUV* as payload (ring module). The *LRS* releases the *nanoAUV* into the water column using a robotic arm with a soft robotic gripper. The *ABL* is divided into two components. One is in the melting probe, the other in the *nanoAUV*. It measures environmental scientific data and analyzes water samples taken by the *nanoAUV*. Moreover, the *LRS* acts as a beacon and communication relay for the *nanoAUV* during the mission. A Command and Data Handling System (CDHS) is implemented at the site of the *Surface Station* for monitoring and commanding the TRIPLE system.
The complete TRIPLE system[2] is planned to be demonstrated at Neumayer III Station (Antarctica) on the Ekström Ice Shelf in spring 2026. The demonstration concept is depicted in Fig. 3. The final TRIPLE system will be demonstrated in Antarctica's Dome-C region in spring 2028.

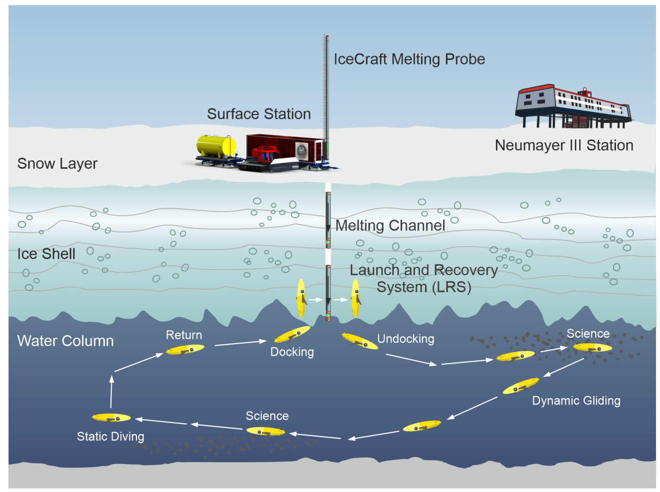

Figure 1. Planned demonstration of the TRIPLE system at the Neumayer III Station (Antarctica).

The nanoAUV: The transport of the *nanoAUV* through the ice shell in the payload bay of the *LRS* limits the vehicle dimensions to a length of 50-80 cm and a diameter of 10-13 cm and thus requires a high degree of miniaturization and integration. The vehicle is pressure-compensated and can be used up to an ambient pressure of 400 bar. It has an impeller drive with thrust vector control, hydrodynamic surfaces, a buoyancy engine, and a mass shift unit. It enables active or passive propulsion with up to $1\,\mathrm{m\,s^{-1}}$ and static or dynamic depth changes. For autonomous under-ice operation, the *nanoAUV* has a miniaturized USBL, which is integrated into the hydrodynamic and -acoustic optimized "Beluga nose" and has an acoustic range of 300-500 m. The USBL enables positioning and communication with acoustic signals. For state estimation, a DVL, a magnetometer, a depth pressure sensor, a tactical-grade IMU, and, if necessary, a mini-FOG for the yaw-axis and echo sounders are integrated. A miniature CTD, a sample collector, and a camera are provided as scientific equipment.

The *nanoAUV* implements a sophisticated Guidance, Navigation, and Control (GNC) system. In its minimal configuration, it realizes the following functions:

- Mission Flow Control (State Machine)
- Waypoint Generation for standard underwater maneuvers
- Path and Trajectory Planning
- Guidance algorithms to resolve the under actuation
- Low-Level Control of the Actuators
- High-Level Trajectory Tracking Control

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[1]A blog is found here: TRIPLE-IceCraft expedition to Antarctica
[2]More information can be found here: TRIPLE website