A low-cost surface vehicle for studying the near-terminus region at tidewater glaciers

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***Abstract*—The terminus region of tidewater glaciers is under-explored, yet the processes occurring there are critical to our understanding and assessment of climate-change-induced ice loss, thermohaline structure, fjord-scale dynamics and bio-physical interactions occuring in the glacial bays. This region is hazardous for humans to directly access, necessitating exploration using uncrewed robots. This paper discusses the design, development and deployment of a low-cost remote-controlled surface vehicle for in-situ studies in the near-terminus region. The robot is instrumented with passive acoustic, conductivity-temperature-depth and video sensors, and is able to profile short transects in close proximity to the terminus region. We outline the strengths of the system, the challenges, limitations, lessons learnt and scope for improvement.**

***Index Terms*—Arctic, climate change, uncrewed surface vehicle, marine robotics, tidewater glacier, terminus**

I. Introduction

Changes in ocean forcing and atmospheric-driven melting of ice-sheets and glaciers have been significant drivers of frontal ablation at tidewater glaciers in recent years [1]. At tidewater glacier termini, ice is lost through submarine melting and calving, which is the mechanical loss of ice from the edges of glaciers and ice shelves. There is uncertainty in the relative contributions of these ice-loss mechanisms, and their spatial variability across the glacier face [2], [3]. The region at the glacier terminus where ablation occurs is under-explored and under-sampled. In order to better understand ablation processes, many unquantified physical parameters that influence ice-ocean interactions require better measurement and bounding, such as the following:

- **Subglacial discharge plumes**: At locations of subglacial discharge, turbulent plumes are generated which locally increase the submarine melt by up to an order of magnitude as compared to regions outside the plume [4]–[6]. There is considerable uncertainty in the location, size and discharge rate of these plumes, as well as their impact on the submarine melt rates, which complicates assessment of frontal ablation at the termini.
- **Morphology**: The morphology of the submerged part of the terminus is relatively unstudied [7].
- **Sound production**: Submarine melting releases bubbles which generates a depth-dependant sound in the glacial bay [8], which has been confirmed with experimental studies using sampled blocks of glacier ice [9]. By using environmental and acoustic propagation physics-based modeling, the sound produced at the glacier terminus can be estimated from ambient sounds recorded in the outer bay [10], but these estimates, as well as the sound's depth-dependence, have not been confirmed with in situ near-terminus measurements.
- **Bubbles**: The bubbles produced during terminus melting may be entrained in the meltwater, enhancing the melt rate [2] and further distorting the acoustic field, but the density and production rate of bubbles in this region remains unquantified.

This paper discusses the design and development of an uncrewed surface vehicle for near-terminus measurements of some of these physical parameters. Uncrewed robots have been successfully used for near-ice operations at polar regions previously [11]–[15]. Examples of prior robotic operations in this region include the use of surface vehicles for bathymetry and hydrographic measurements [6], [16]–[18], autonomous underwater vehicles for sonar, video and oceanographic observations [19], [20], and drone-deployed autonomous conductivity-temperature-depth (CTD) profilers operating near the terminus [21], [22].

Robotic operations near glacier termini have been few, because of the danger from calving activity in these regions, and the high cost of repairing or replacing robots affected by this hazard. Additionally, calving complicates accessibility at the terminus by choking the glacier bay with thick ice-mélange, preventing surface movement. Due to the hazards involved in operating near the glacier terminus, simple, robust and low-cost robotic systems capable of making measurements allow for low-risk studies at the terminus. To enable this study and fill observational gaps, we developed a low-cost, remote-controlled surface vehicle, the "glacial frontal ablation monitoring robot" (GLAMOR), for in-situ studies in the near-terminus region. The vehicle was deployed during field trials in Hornsund fjord, Svalbard, during July 2023. This paper discusses the design, development, and deployment of this vehicle and its sensor payloads. Section II describes the GLAMOR system, including its development requirements and principles, capabilities, sensor payloads and pre-deployment testing results. Section III details the deployment of the vehicle near glacier termini during a field campaign in Svalbard in 2023. Section IV describes the different sensor data collected and a preliminary analysis of the data, and section V concludes the paper, drawing learnings, summarizing the strengths of the system, and outlining limitations and scope for improvements.

II. System description

A. Development requirements and principles

The GLAMOR was developed with the aim of collecting acoustic, oceanographic, and video data near the terminus. The primary mission requirements were that (1) it would be remote-controlled with a range of at least 200 m so that the operator could be stationed outside the dangerous calving zone, (2) it would be low-cost, and there would be multiple backup systems, (3) it would be a low-weight system for easy deployability, handling, and retrieval in the glacial bay, due to unpredictable conditions that often require deployment flexibility. The system would need to be robust in terms of (1) mechanical stability, in order to handle the changing marine environment with floating ice, currents, and calving, (2) control systems, with on-oboard automated return to a safe home-point or, to preset station points upon loss of communication with the operator, (3) thruster operation, to avoid getting stuck (4) a streamlined body with few concave edges which increase the chance of line entanglement. Additionally, a modular vehicle design, configurable for additional user-defined sensor payloads, was desired.

B. Vehicle description and capabilities

The GLAMOR was built by modifying an off-the-shelf Chasing F1 Pro surface robot originally designed for fish-finding [23]. The vehicle is controlled over WiFi at both 2.5 GHz and 5 GHz bands. The vehicle navigation and control requires either a hand-held remote-controller or an app from Chasing installed on a smartphone. The vehicle has a remote controlled line winch onboard for light-weight sensor depth-profiling. The line winch has a vertical speed of about 0.3 m/s, with a maximum length of 20 m, with a terminal end connection for an underwater camera with real-time video monitoring capabilities. The navigation system does not allow pre-programming of survey tracks, but does allow the setting of GPS waypoints during a mission in order to allow the GLAMOR to return to a chosen location. These waypoints can be used for repeating survey tracks done in previous mission iterations.

The Chasing F1 Pro is $278 \times 154 \times 215$ mm in dimensions, and is powered by a rechargeable battery with capacity of 51.8 Wh. The vehicle has a plastic ellisoidal hull housing the electronics. It is capable of speeds of up to 0.5 m/s while towing the buoyancy collar, and each battery has about 3 hours of endurance when continually thrusting. The system also has an underwater light and a bow light, and comes with a towable payload attachment (originally meant to carry fish feed). The complete system weighs less than 2 kg, making deployment and retrieval easy.

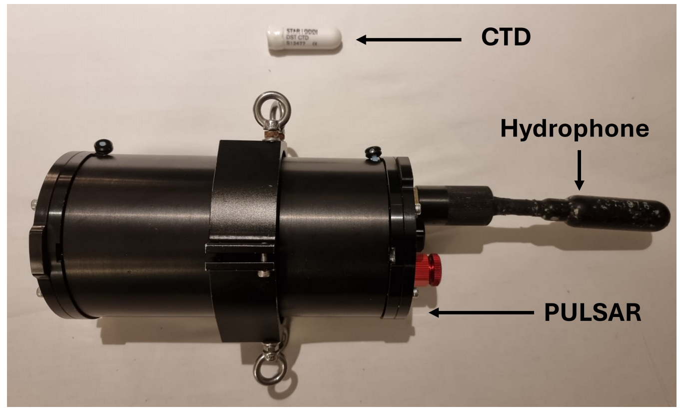

Fig. 1: Close-up photo of the PULSAR with hydrophone attached, and the CTD.

During initial tests conducted at a reservoir in Singapore, the range of the WiFi remote control system was found to be inadequate for the required operation. The 2.5 GHz band provided 83 m of operational range, and the 5 GHz band provided 120 m range in calm sea-surface conditions. In order to extend the range of operation, the operator receiver was supplemented with a directional WiFi antenna (TPLink). Tests with the extender provided an operational range of more than 300 m in calm conditions, which was deemed adequate for the safety of the system and operator. During testing, we also found that the Chasing's battery holder was not mechanically stable and did not have a mechanism to lock the battery solidly into place. Thus, the battery containment was reinforced with waterproof tape for strength and to ensure the battery stayed in place.

Chasing provides a smartphone app that displays the GPS coordinates of the vehicle, but as of the time of writing this paper, does not provide a method to log the GPS data during vehicle missions. In order to provide this capability, we developed custom optical character recognition software to extract GPS data from screen recordings of the Chasing app running on the cellphone. The character recognition algorithms extract the time-synced GPS data while post-processing the app recordings after mission operation.

C. Sensor payloads

The sensors mounted directly onto the GLAMOR included:

1) CTD logger: A mini stand-alone CTD from Star-ODDI with in-built power was used [24](close-up photo in Fig. 1). It has a cylindrical shape and is small enough (5 cm length, 1 cm diameter) and light enough (21 g in air, 13 g in water) to be attached to the GLAMOR winch system. The CTD comes with a polyurethane plastic protective housing, a separate communication box and SeaStar software that can be used to download recorded data onto a computer, and to pre-program the sensor to turn on at a pre-set date and time, and fix

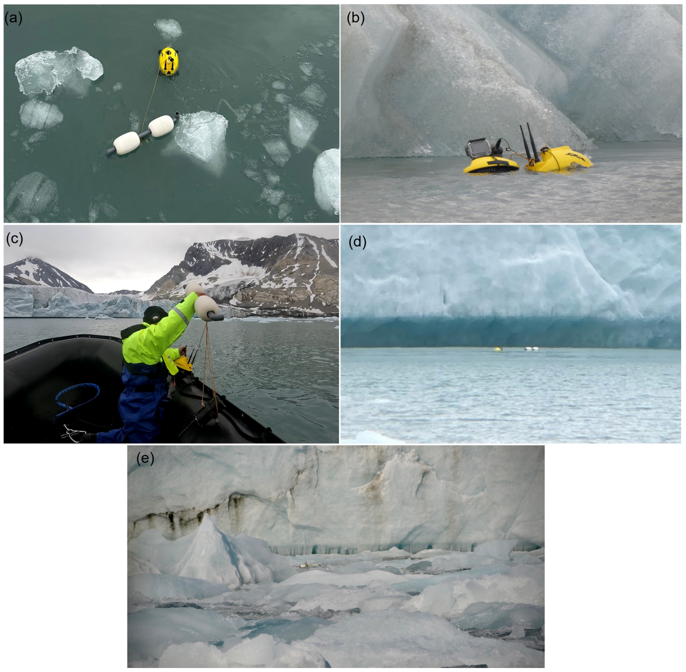

Fig. 2: The GLAMOR with (a) the buoyancy collar and PULSAR mounted below, (b) a towed payload module with GoPro mounted on it scanning a bergy bit, (c) photo of deployment procedure, (d) example where the GLAMOR was beneath a glacier's overhang, (e) thick ice-mélange in the near-terminus region during the GLAMOR deployment

the measurement frequency. A measurement frequency of 1 Hz was selected (which was the highest setting available). The conductivity sensor has a range of 3-68 mS/cm, resolution of 0.025 mS/cm and accuracy of 1.5 mS/cm. The temperature range is -1 to 40°C, with a resolution of 0.032°C, accuracy of ±0.1°C, and a response time constant of 20 seconds. The STARODDI is available with several standard depth ranges, of which we opted for a depth range of 100 m with a resolution of 0.03 m and accuracy of ±0.6 m.

2) Underwater camera: The Chasing system is provided with an underwater pan-and-tilt camera that can be operated via the app software. The camera captures photos at a resolution of 1920×1080, and can record video in either 1080P or 576P resolutions at 30 frames per second [23]. It has a pan angle of ±173°, tilt angle range of $-27°$ to 75°, field of view of 164.6°, focal length of 2.7 mm, lens aperture of 5.4 mm and ISO range of 100-102400. The camera footage is transmitted in real-time to the operator. This camera cannot be directly replaced by other commercially available cameras at this time. Thus, using a separate underwater recording camera would require mounting an autonomous battery-powered camera onto the GLAMOR system separately, without the possibility of real-time viewing.

Additionally, the GLAMOR towed a sensor payload. During the Hornsund fjord deployment we towed the following two sensors on GLAMOR:

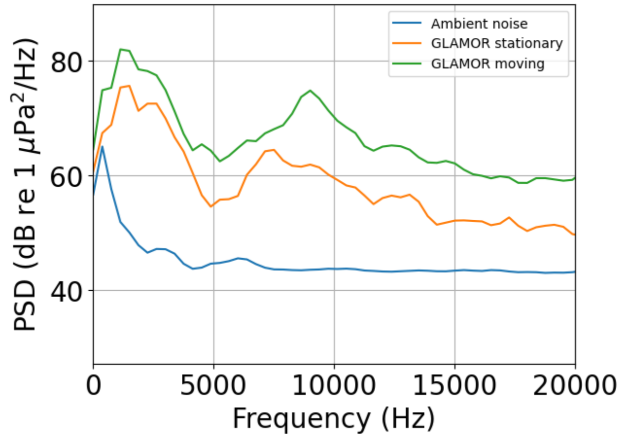

Fig. 3: PSD of recorded noise from GLAMOR during tests when it was stationary and moving.

1) Passive acoustic recorder: We developed a passive, ultra-light, stand-alone acoustic recorder (PULSAR) to record near-terminus acoustics in order to validate the magnitude of sound generated at the glacier face, study its spatial variability, and correlate it with other physical parameters such as subglacial discharge, melt rate and morphology. The PULSAR was a stand-alone acoustic recorder, developed from a single HTI 96-min hydrophone and a Loggerhead Systems acquisition board capable of autonomously acquiring acoustic data at 96 kHz sampling rate (close-up photo in Fig. 1). The hydrophone had a sensitivity of -180 dB re 1V/μPa, and a preamp with a gain of 16.8 dB. The board had a 256 GB SD card to store the recorded data, and was powered by a USB power bank, providing an endurance of up to 3 days of continuous recording. The entire system was fit into a 7.6 cm diameter Blue Robotics watertight bottle and was negatively buoyant.
Prior to the deployments, the acoustic interference from the thruster operation was characterized in a test tank (Fig. 3). The interference peak at 81 dB re1μPa^2/Hz is at a frequency of approximately 2 kHz, which overlaps with the frequency band of interest for submarine melting (1-3 kHz) [8]. The acoustic interference's magnitude and center frequency increased with increasing thrust, by an average of 3.1 dB within the 1-3 kHz band. In [8], the power spectral density (PSD) of sound from the terminus melting was measured to be around 100 dB re1μPa^2/Hz at 2 kHz at Hansbreen, and that of a nearby growler was found to be 105 dB re1μPa^2/Hz at a range of approximately 20 m. Thus, based on the tests, the magnitude of the thruster sound during operation was not expected to be significant compared to the overall sound from submarine melting, especially if recorded from near the terminus. Nevertheless, the thrusting was

periodically stopped and the vehicle was allowed to drift in order to minimize interference from the thrusters during acoustic recordings.

The PULSAR was mounted onto a custom-built buoyancy collar towed behind GLAMOR. The buoyancy collar consisted of dual foam floats cross-connected by a PVC pipe, below which the PULSAR was mounted at the desired recording depth. The system was mechanically stable, and allowed for towing by the GLAMOR at its highest speeds based on field tests. The tow rope connection between the GLAMOR and PULSAR was approximately 1 m, to minimize both the risk that the tow rope could become entangled in the thrusters, and the acoustic interference from the thrusters. Previous studies in Hornsund fjord indicated that the sound of melting glacier ice is loudest near the sea surface, and reduces with depth down to about 13 m [9] as per studies at Hansbreen glacier, but these properties could vary at different glaciers. With this in mind, the PULSAR was positioned so that the hydrophone depth was approximately 2 m below the sea surface.

2) Surface-mounted camera: A battery-powered GoPro camera was attached onto a towed-payload module above the surface, providing video footage of the terminus regions traversed by the GLAMOR.

Table I gives details on the endurance of the different subsystems of the GLAMOR.

III. Deployment

Field campaigns were undertaken in 2023 in Svalbard to record visual [25] and acoustic data near the glacier termini. Here, we describe the deployments at Hornsund fjord, Svalbard, which were staged from the Polish Polar station. GLAMOR was deployed in the bays of two tidewater glaciers, Hansbreen and Paierlbreen (Fig. 4). During these deployments, GLAMOR was deployed from a Zodiac boat crewed by three or four people - a boat driver, GLAMOR pilot, and one crew spotting to aid vehicle deployment/retrieval, visually monitoring the robot during missions, and ensuring WiFi connectivity via the directional antenna.

Immediately prior to deployment, the PULSAR and CTD were switched on to record data continuously until retrieval at the mission end. The PULSAR was mounted onto the buoyancy collar, and the CTD onto the vehicle winch. The WiFi connectivity from cellphone to the WiFi antenna, and antenna to GLAMOR was checked, and screen recording of the phone app was started for data logging and eventual post-processing of the GPS data.

The GLAMOR and sensor payload were transported by Zodiac boat to the safety radius of $\sim$200 m surrounding the location of interest at the terminus. Locations along the glacier terminus picked for deployments were primarily where surface expressions of subglacial discharge outflows or severe undercutting at the terminus ice face were observed, to coordinate with parallel studies being done using active acoustics. The motivation here was to record the spatial variability in the acoustic and thermohaline signature in these melting zones. These may be caused due to the presence of discharge plumes which are known to increase localized melting [5]. The surface track of the sensor-traversed area was planned such that we would be able to cover at least the width of the surface expression of the plume. One of the dominant factors in determining the deployment location was the absence of thick ice-mélange, because the GLAMOR's progress through mélange was very slow or sometimes impossible (eg. Fig. 2(e)). Thick ice mélange also made retrieval risky because it can also hinder the Zodiac's navigation. During GLAMOR missions, line of sight from the WiFi antenna to the GLAMOR was preferred for robust connectivity.

During operation, the GLAMOR transects were planned to span 50-100 m along-fjord (perpendicular to the terminus face), as well as parallel to the terminus ice face, depending on operational constraints. The small surface expression of the GLAMOR and the sensor payload often made visual tracking difficult, requiring of the use of binoculars to provide feedback to the pilot on the vehicle's movement. Surface currents induced by strong glacier outflows also sometimes impeded the vehicle's mobility and presented a challenge to operation, but this was mitigated via a combination of appropriate choice of deployment location and careful navigation. During the deployment and the sensor scan, safe GPS homing points were set by the pilot for the GLAMOR to automatically return to in case of the loss of WiFi connectivity. At points of interest, the vehicle was stopped and allowed to drift, and the winch was lowered so that a CTD profile and subsurface video profile of the location could be obtained.

At mission end, retrieval was accomplished by piloting the GLAMOR away from the terminus and towards a surface location where retrieval could be done safely and conveniently by the zodiac crew. When visibility of GLAMOR was not clear, the automatic return-to-home functionality was used to initiate the vehicle's navigation away from the terminus until it was visible.

During some deployments, there were large calving events nearby (as close as 100 m), creating large swells and thick mélange, but the vehicle was able to stably and safely ride through these surface hazards.

IV. Data collection

Data were collected from eleven transects over six deployment days, each spanning around 200 m in length within 80 m of the terminus. In three of these transects (e.g. shown in Fig. 2(d), Fig. 4(b) and (c)), GLAMOR was operated directly beneath or next to the overhang at the glacier face. The following types of data were collected:

1. Acoustic data: The system was able to successfully collect acoustic data from the terminus region. An example of a recorded timeseries from the PULSAR is shown in Fig. 5(a). In order to characterize the impulsiveness of the timeseries, a symmetric α stable probability density is fit to the data [26]. In this example, a best-fit α value of 1.88 was obtained which

Subsystems	Power source	Battery endurance	Data storage device	Recording duration
Navigation, control	Chasing battery	3 hours	-	-
Underwater camera	Chasing battery	(dependent on navigation speed)	Chasing microSD card	Around 500 hours (continuous video recording)
PULSAR	Power bank	3 days (continuous recording)	Dedicated microSD card	30 days (continuous recording)
GoPro camera	GoPro battery	2.5 hours (continuous recording)	Dedicated microSD card	6 hours
CTD sensor	Internal battery	5.5 days (for sampling interval of 1 Hz)	Internal EEPROM storage memory	24 hours (continuous recording at 1 Hz)

TABLE I: Endurance specifications of different subsystems

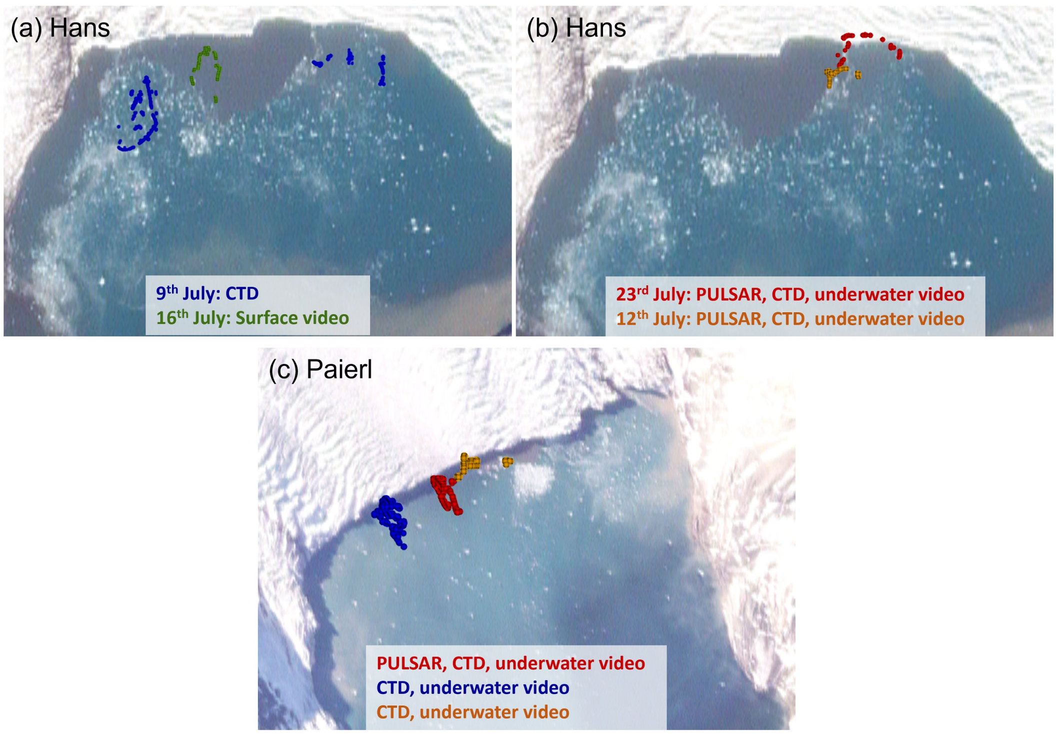

Fig. 4: GPS tracks of GLAMOR deployments at (a) and (b) Hansbreen terminus, and (c) Paierlbreen terminus. The background maps were obtained from www.planet.com, Planet Labs PBC, under a CC BY-NC-SA 2.0 license.

suggests more impulsiveness in the noise recording due to the close proximity to the terminus face.

2. Thermohaline data: The system obtained CTD profiles in the near-terminus region. Profiles were obtained both (i) horizontally (along the glacier face and perpendicular to it) with the CTD sensor at a fixed depth, as well as (ii) vertically down to depths of 20 m using the GLAMOR's winch while the vehicle held station in terms of horizontal position. The data clearly showed the presence of a near-surface, cold, glacially-modified, water layer of low salinity due to ice melt, stratified above the warmer and more saline Atlantic waters. Note that the DST Star-ODDI miniature CTD was removed from its manufacturer-provided secondary plastic housing and attached directly to GLAMOR winch line to significantly improve its sensor response time and accuracy. This was then linearly calibrated to data obtained from a Valeport miniCTD sensor to correct for bias, as shown in Fig.6.

3. Underwater video: In total, eleven vertical profiles were done with the underwater video camera. The camera had an infrared light source, which was crucial for visibility at depths greater than 5 m. This was useful in capturing the presence of suspended bubbles at depths down to 20 m (Fig. 5(d)). This observation holds significance in the context of modeling ablation at the terminus, as bubbles are shown to increase the melt rate [2]. The near-surface video from 0.5 m depth can also enable estimation of size distributions of bubbles that reach the surface, adding to an understanding of bubbles in the near-terminus region.

4. Surface video: Two deployments were done to obtain in-air GoPro video data using the GLAMOR. On one run, a growler was surveyed with video, and one run was near the terminus region where we scanned along the terminus to obtain video with the aim of studying the surface morphology of the glacier front (Fig. 4(a), Fig. 5(c)).

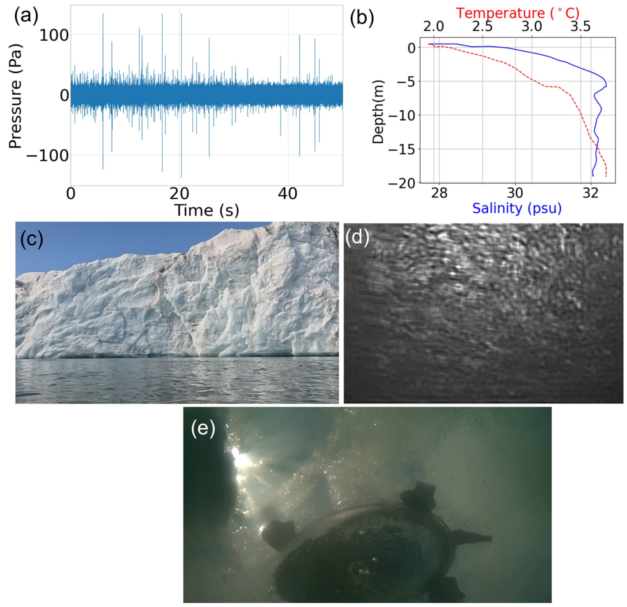

Fig. 5: Sensor measurements using the GLAMOR: (a) 50-s acoustic timeseries, (b) Temperature (dashed) and salinity (solid) data from one transect, low-pass filtered to remove oscillations, (c) a video frame from the surface-mounted GoPro, (d) processed image from underwater camera showing bubbles in the water and (e) upward-pointing view from the camera at a depth of 0.5 m, showing the GLAMOR surrounded by ice-mélange.

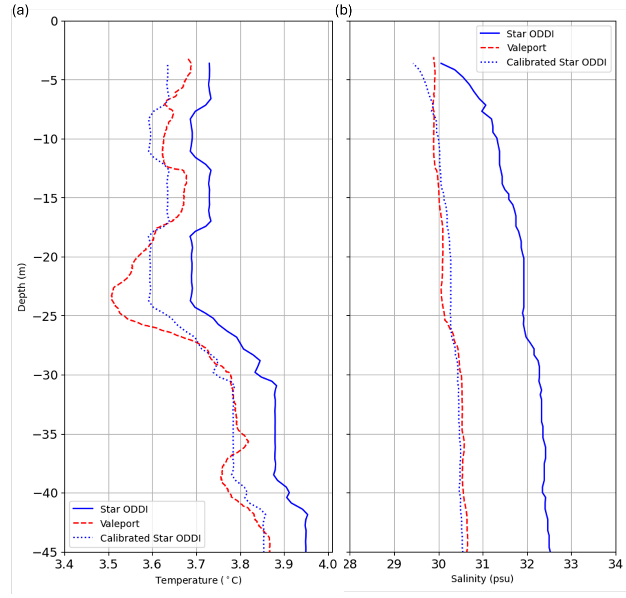

Fig. 6: Calibration of DST Star-ODDI CTD against Valeport CTD sensor for (a) Temperature, and (b) Salinity measurements. The solid blue line shows the original measurements by the Star-ODDI CTD, and the dotted blue line is the Star-ODDI measurement calibrated against the Valeport sensor. The Star-ODDI data was low-pass filtered prior to calibration to reduce quantization noise. Near-surface depths (<4m) are not considered in the calibration because they are very noisy.

V. Conclusions

The GLAMOR system provides a robust and low-cost option for studying the glacier terminus-ocean interface. This system can elucidate ice-ocean interactions in this less-studied, challenging region, including but not limited to: the thermohaline properties, the size and velocity of turbulent plumes and subglacial discharge, the sound produced at the terminus, the distribution of bubbles released due to melting, and the underwater morphology of the ice front. Furthermore, GLAMOR enables sensing of the near-terminus region via different modalities (e.g. vision, acoustics, temperature, salinity), which can be integrated and compared for a more comprehensive study of the glacier terminus region.

Despite challenges posed by the rigors of the glacier environment, including nearby calving activity, low temperatures, the presence of ice-mélange and rapidly-changing weather conditions, all of which affected both vehicle control and navigation, the vehicle was able to successfully achieve its mission parameters. The system is small, inexpensive, and portable, and does not require drone-based deployment. Though the vehicle itself cannot directly access the subsurface region as autonomous underwater vehicle-based field surveys can (eg. [19], [20]), this allows it to be controlled remotely, keeps the navigation and control systems simple and allowing real-time video streaming. Consequently, this enables adaptive maneuvering of the vehicle to survey regions of interest. Furthermore, through effective design and planning, sensing of the underwater regions of interest was possible through a combination of placement of sensors at the right depth and use of the winch. The overall cost of the GLAMOR system (including underwater camera and winch) was USD 1200, and, with the addition of the STARODDI CTD and the PULSAR systems, the total system's cost was approximately USD 4000 excluding the cost of the GoPro camera and personnel-hour costs for development. In this sense, it was able to achieve its objective of affordability and portability, which was our primary objective.

Careful planning and testing of the system to understand its limitations beforehand was crucial to helping achieve these goals. Some additional system parameters that helped support the mission objectives include:

1) The GLAMOR provided good mechanical stability, and its ellipsoidal hull design worked very well in the environmental conditions encountered. This design ensured that when the vehicle was contacted by floating ice from the sides, rather than getting crushed or submerged, it was pushed upwards from the water and stayed afloat. There were a few cases where large ice blocks calved from the terminus nearby (as close as 100 m), the vehicle was able to safely ride through the resulting swells and mélange.
2) Though there was occasional loss of WiFi connectiv-

ity to the vehicle, particularly in cases where icebergs blocked the line-of-sight from the pilot, the automatic homing system of the robot helped quickly regain control and visibility of the craft.
3) The real-time video stream from the vehicle provided some sense of surroundings for the pilot to control the vehicle, and also provided immediate access to the underwater video data, which was one of the objectives of the campaign. By creating a screen recording of the Chasing app we ensured that we had a backup of the video data and GPS locations, even in case of the vehicle getting irretrievably lost or damaged.

One of the biggest limitations of the system was its payload capacity, which was a limitation imposed by its size. Nevertheless, design of the payloads and tow-floats allowed us to tow sufficient payloads to achieve mission parameters. The limited thruster strength also meant that the vehicle could get stuck in thick ice-mélange, and would find it hard to drive its way through fast surface currents or eddies which could sometimes trap the vehicle or prevent it from moving towards the area of interest. At Hansbreen, surface current velocities of upto 0.15 m/s have been observed [27], and in places such as Greenland currents of upto even 0.5 m/s have been observed [15], which poses a challenge to the operation of the vehicle.

Furthermore, the limited length of the winch means that we cannot get a full picture of the thermohaline properties down to larger depths at the terminus. The maximum winch length could also be a limitation in locations where the maximum acoustically active depth at which underwater melting produces sound significantly exceeds 20 m. It has been shown in previous work [9] that at Hansbreen glacier in Hornsund fjord, the maximum acoustically active depth of melting glacier ice blocks is about 13 m, though this could be different for different glaciers. As such, a winch line depth of 20 m was deemed adequate to capture the information necessary to study the sound produced at the glacier termini in the region studied in our field trials.

Improvements we envision to this system include:

1) An independently-powered GPS module with satellite communications transmitter located on top of the vehicle, which can provide a constant update of its location. This would allow us to locate the vehicle even in scenarios where connectivity to the GLAMOR is lost, as long as it is floating on the surface. For example, during one of the deployments, the GLAMOR got trapped in a thick ice-mélange (Fig. 2(e)), ran out of battery, and had to be abandoned. However, within 24 hours, it was pushed by tidal currents to a nearby beach with all its sensors intact and recording, providing about 22 hours worth of data. While this clearly demonstrated the mechanical stability and robustness of the system, it also showed the importance of having a redundant GPS beacon which would have allowed us to locate and retrieve the vehicle as soon as it was free of the ice-mélange.
2) Painting the foam floats on the buoyancy collar a more prominent color (e.g. red, orange), which would also make it easier to spot and distinguish visually from ice, snow, and reflections on the water surface.
3) Real-time streaming of other recorded data, such as the acoustics and CTD data, to the operator, which would provide valuable assistance in piloting the vehicle and also ensure that valuable mission data would be available immediately even if the vehicle were to be lost.
4) Incorporating other measurement systems that may be of interest, including but not limited to turbidity sensors and depth-finding sonars. Other sensors can be mounted onto the GLAMOR as long as they are autonomously powered and recording and do not disrupt the stability and navigation capabilities of the vehicle.

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