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A low-cost remotely operated vehicle (ROV) with an optical positioning system for under-ice measurements and sampling

Lars Chresten Lund-Hansen[a,b,*], Thomas Juul[c], Tor Dam Eskildsen[c], Ian Hawes[d], Brian Sorrell[a,b], Claus Melvad[c], Kasper Hancke[a,e]

[a] *Aquatic Biology, Department of Bioscience, Aarhus University, Build. 1134, Ole Worms Allé 1, 8000 Aarhus C, Denmark*
[b] *Arctic Research Centre, Department of Bioscience, Aarhus University, Build. 1540, Ny Munkegade 114, 8000 Aarhus C, Denmark*
[c] *School of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus C, Denmark*
[d] *Coastal Marine Field Station, University of Waikato, Sulphur Point, Tauranga 3110, New Zealand*
[e] *Norwegian Institute for Water Research (NIVA), Research Centre for Coast and Ocean, Gaustadalléen 21, N-0349 Oslo, Norway*

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ABSTRACT

Here we describe the design, performance and field tests of a lightweight (13.1 kg), low-cost (15.000 USD), and portable remotely operated vehicle (ROV) of dimensions 55 × 43 × 34 cm (L × H × W), with a new optical based positioning system. The ROV is designed for deployments and measurements of the irradiance field at a short distance below sea ice bottom in landfast level sea ice at calm under ice conditions. It is equipped with two cameras (front and rear) for optical positioning based on reference poles with LED lights below the ice. A third upward camera is for guiding during deployment and positioning. The ROV is equipped with spacer poles to maintain a constant distance between ROV with onboard optical sensors and bottom of the ice. All pre-tests of housing, thrusters, optical positioning, and ROV maneuverability were carried out in freshwater basins prior to field trials and tests. These were conducted at Kangerlussuaq, West Greenland on landfast first-year 79–80 cm thick ice with a variable (1–12 cm) snow cover in March 2016. The ROV was easily deployed through a hole (75 × 50 cm) in the ice and easy to maneuver below the ice. Test of positioning system showed an average deviation of 28 ± 5 cm between optically based position and actual position with an average offset from center line of 16 ± 5 cm. The ROV was applied for measuring the under-ice irradiance field and results demonstrated a solid negative correlation between snow depth and PAR transmittance. We derived a Normalized Differences Index (NDI) for snow depths: $\mathrm{NDI}_{\mathrm{snow\ depth}} = [E(610\,\mathrm{nm}) - E(490\,\mathrm{nm})]/[E(610\,\mathrm{nm}) + E(490\,\mathrm{nm})]$ with minimum attenuation at 490 nm and maximum at 610 nm. It is discussed that the correlations for both PAR transmittance and the NDI with snow depths are due to a combination of a constant distance between optical sensor and ice bottom, and accurate positioning. A test showed that the wakes of thrusters removed parts of the ice algae biomass, but the study demonstrates the applicability of this ROV design for measurements of the under-ice irradiance field below landfast sea ice with a new optical based positioning system.

1. Introduction

A variety of Remotely Operated Vehicles (ROVs) have been used in the polar regions for research either using ship based platforms, or operated directly from the ice through a hole, or in leads in the ice. ROVs are particularly well-suited for under-ice missions in that they allow access to an area/environment otherwise difficult to access, and minimize disturbance of the ice environment compared to traditional coring methods. ROVs further enable operations across a range of temporal and spatial resolutions, and perform measurements of key under-ice variables that would be difficult to obtain by any other methods (Moore et al., 1986; Christ and Wernli, 2013). ROV-based research in polar regions has been applied for assessing the spatial variability of sea ice thickness (Wadhams, 2012), for physical, chemical and biological water sampling close to icebergs (Hobson et al., 2011), study their micro algae communities (Robison et al., 2011), and Antarctic benthic communities (Cazenave et al., 2011). At the ice-water interface ROVs have been deployed for imaging of ice algae (Ambrose et al., 2005), ice algae aggregates (Katlein et al., 2015a), for mapping under-ice irradiance, transmittance, and ice algae distributions (*e.g.* Mundy et al., 2007; Nicolaus and Katlein, 2013; Bowen et al., 2014; Katlein et al., 2015b; Lange et al., 2016; Taskjelle et al., 2016; Arndt

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[*] Corresponding author at: Aquatic Biology, Department of Bioscience, Aarhus University, Build. 1134, Ole Worms Allé 1, 8000 Aarhus C, Denmark.
E-mail address: lund-hansen@bios.au.dk (L.C. Lund-Hansen).

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et al., 2017; Katlein et al., 2017; Meiners et al., 2017). An advantage of ROVs over traditional techniques of through-hole sampling is their ability to obtain measurements and images across large spatial scales and non-invasively, in contrast to the traditional invasive drilling of ice cores with limited spatial resolution. Transmittance through the ice and irradiances at the bottom of the ice are the main parameters explaining the spatial distribution of ice algae, with their photosynthesis being limited by irradiance and less by nutrients (Arrigo and Sullivan, 1994; Mundy et al., 2005; Arrigo et al., 2010). Under-ice irradiance is regulated by the optical properties of the ice and snow (*e.g.* Perovich et al., 1998; Nicolaus and Katlein, 2013; Lund-Hansen et al., 2013; Katlein et al., 2015b; Taskjelle et al., 2016) and studies have established negative relations between snow depth and ice algae biomass (Juhl and Krembs, 2010; Mundy et al., 2005). There is, in this respect, a need for more detailed and accurate measurements and descriptions of under-ice PAR and spectral transmittance distributions that can be applied in the Arctic primary production models. Achieving this also requires replacement of the standard core-based point-sampling method of PAR and spectral transmittance based on through-hole and L-arm techniques (Lund-Hansen et al., 2013; Lange et al., 2016). For ROV-based remote sensing of snow and sea ice transmittance, it is specifically required that under-ice PAR and spectral irradiance can be obtained at accurate positions. ROVs flying depths for under-ice irradiance is typically 1–2 m below the bottom of the ice (Katlein et al., 2015b; Lange et al., 2016). Under-ice transmittance has been mapped with constant distances between sensor head and the ice but with no precise positioning and reduced maneuverability (Nicolaus et al., 2013; Taskjelle et al., 2016). The radiometer sledge developed by Nicolaus et al. (2013) with a constant distance between ice and sensor head of 2 cm had a positioning accuracy of < 1.0 m. We have constructed a novel, lightweight, and very low-cost ROV equipped with a new positioning system that allows decimeter-scale positioning accuracy over underwater transects of at least 15 m. The ROV is easily deployed through a hole in the ice and can place optical instruments at a precise and constant vertical distance to the bottom of the ice at all positions using spacer poles. The ROV was designed and developed for landfast level sea ice and here we describe the ROV, validate its positioning accuracy, and demonstrate its use for obtaining PAR and spectral transmittance under landfast level sea ice at Kangerlussuaq, West Greenland.

2. Materials and procedures

2.1. ROV design

The outer frame of the ROV was a blend of polycarbonate and aluminum parts on which the thrusters and canister were mounted (Fig. 1a–c). Dimensions of the ROV were ($55 \times 43 \times 34$ cm L × H × W) with an in-air weight of 13.1 kg. The canister was custom-made from milled aluminum and acrylic pipe, and housed the electronics and the three cameras. The main floats (yellow) were made of extruded polystyrene with closed cell structures for buoyancy. Additional floats made of polyethylene foam material (grey) and also with closed cell structures were mounted on site to trim the ROV to keep a weak positive buoyancy (Fig. 1a). At position the ROV drifts towards the bottom of the ice with thrusters turned off in order not to cause any disturbance of the ice algae. Vertical thrusters were turned on when leaving the position to circumvent the weak positive buoyancy. The ROV was powered through the tether by an external power supply (here we used a gasoline driven Honda EC2000 2.0 KW). The ROV was equipped with three cameras: one for recovery (Pointgrey Blackfly, BFLY-PGE-12A2C-CS, 1280×960 pixels) and two for positioning (Pointgrey Blackfly, BFLY-PGE-50A2C-CS (2592×1944), Richmond, BC, Canada, http://www.ptgrey.com). The positioning cameras were mounted with lenses (Fujifilms, Fujinon HF9HA-1B, Tokyo, Japan, http://www.fujifilmusa.com), with one facing forwards and one backwards for positioning and direct visual feedback (Fig. 1a–c). The third camera was facing upwards and equipped with a fish-eye lens (Lensation, Lensagon BF5M13720, Karlsruhe, Germany, http://www.lensation.de) and used to maneuver the ROV during deployments and recovery. Maneuvering was executed with six thrusters (Blue Robotics T200 Thrusters, Torrance, California, U.S., http://www.bluerobotics.com), with four of the thrusters mounted in a vectored configuration. A configuration where the length axis of the thrusters is oriented 45° relative to the center axis of the ROV for optimum control and stability in the horizontal direction. The remaining two were oriented vertically for pitch, roll, and depth control. An auto-depth module, which operates *via* the onboard pressure transducer (Type 4130A0.2, Kistler, Herfølge, Denmark, http://www.kistler.com), maintained a constant depth at horizontal movements. The vertical thrusters were placed underneath the housing to minimize any influence of the wake of the thrusters during operation and deployments (Fig. 1c). A control room was set up in a tent on the ice where an operator maneuvered the ROV based on live-feed information from the three ROV cameras, depth recordings, and positioning data (Fig. 1d). A group of five persons tested the ROV at several sites and it took about one hour to drill the hole in the ice, set up the control room, and place the LED reference poles at each end of the transect of interest. All control of the ROV was manual, using a X-box Controller (Wired USB gamepad controller for Microsoft Xbox 360, http://www.microsoft.com). Navigation data comprised three live-feed signals from the cameras, depth, and output data from the positioning system. Data were displayed and processed on a laptop PC, in a program developed by the authors using LabVIEW's Real Time Module (LabVIEW, Austin, Texas, USA, http://www.ni.com). The electronics in the housing were kept above freezing point by the generated heat from the internal DC-step-down voltage converters. A tether facilitated electric power to the ROV, and data transmission (Ethernet) between control room laptop PC and ROV. The tether consisted of three separate cables bundled into one with cable ties around a metal wire. Small floats were mounted at about every 1 m along the tether to keep neutral buoyancy and minimize drag. The ROV was parked at positions under the sea ice with the spacer poles resting against the bottom of the ice, which ensured a constant and small distance between optical sensors and the ice at all positions (Fig. 1c). The weak positive buoyancy of the ROV allowed the spectroradiometric measurements to be carried out with all thrusters turned off and the ROV parked at constant positions below the ice. The maximum ROV working range was initially developed and designed to 30 m but was changed to 15 m during tests due to unexpected high attenuation in the water (Fig. 1d). The ROV was kept in a heated and insulated box between deployments in the control room. This was to prevent freezing of water around thrusters, which might be damaged at the low air temperatures (minus 5–20 °C). The total material cost was about 15.000 USD. Technical details concerning brands, specifications, and calibration of the positioning system can be found as Supplementary Material.

2.2. Positioning system

Reference poles with LED lights were mounted through holes in the ice at either end of an experimental transect for positioning of the ROV (Fig. 1b–d). The poles were constructed of polyoxymethylen (POM) to prevent freezing into the ice as we had to relocate between different test sites and remove poles. Each pole contained two LEDs in aluminum housing for protection, and to ensure a high thermal conductivity of generated heat by the LEDs, in order to avoid any damage of the LEDs. The depth of the poles was adjusted by horizontally mounted aluminum rods at the top of the poles (Fig. 1b). The LEDs were powered *via* the surface power supply – the Honda generator. The positioning system was designed to allow the ROV to navigate in 2D with respect to the two reference poles, each equipped with two strong lights visible to the front and rear cameras on the ROV (Fig. 1d). The two reference poles were positioned at each end of the ROV transect with the LED lights