A low-cost survey method for sea ice topography using Structure-from-Motion photogrammetry and small UAVs

Martin St-Amant, Derek Mueller, Adrienne Tivy, and Adam Garbo
1 Water and Ice Research Laboratory, Department of Geography and Environmental Studies, Carleton University, Ottawa, Canada
2 Mapping and Charting Establishment, Canadian Armed Forces, Ottawa, Canada
3 Canadian Ice Service, Environment and Climate Change Canada, Ottawa, Canada

ABSTRACT

Sea-ice topographical measurements are valuable data for sea-ice research, monitoring and engineering design. Current sea-ice topography surveying techniques, such as ground-based surveys, aerial lidar or satellite imagery, all offer trade-offs with respect to accuracy, precision, spatial scale, spatial resolution and cost. Recent technological advancements have enabled the use of Structure-from-Motion (SfM) surveying techniques, coupled with small unmanned aerial vehicles (UAVs), as a low-cost solution for the acquisition of high-resolution topographic datasets. Here, we evaluated the potential of UAV-SfM for the topographic surveying of sea-ice, a unique and challenging environment.

Field data was collected in Frobisher Bay, Nunavut, Canada, and consisted of three sUAV-SfM surveys at the sub-kilometre-level spatial scale over fast ice with multi-metre semi-diurnal tides. Using point-cloud comparisons, vertical RMSE values of 87 mm and 80 mm were obtained, respectively, from comparisons of the sUAV-SfM to a reference dataset obtained using ground surveying techniques, and from comparisons between individual sUAV-SfM surveys. The technique was successful at detecting, measuring and visualizing sea-ice topographical features, such as pressure ridges, from surveys at the sub-km spatial scale. Technical details on equipment set-up and data processing, as well as accuracy, precision and repeatability metrics are presented a resource for prospective sUAV-SfM users with an interest in the observation, monitoring or measurement of sea-ice topography. Potential end-users include sea-ice scientists and engineers, Arctic communities, ice services, polar port operators and icebreaker operators.

KEY WORDS: Sea-ice topography; Structure-from-Motion; UAV.

NOMENCLATURE:

sUAV: small unmanned aerial vehicle (UAV), weighting less than 25 kg

INTRODUCTION

The topography of sea-ice needs to be well known for a variety of applications such as ice-surface trafficability analysis (Dammann et al., 2018), ice movement predictions (Steiner et al., 1999) and ice-thickness estimations (Doble et al., 2011). Common topographical surveying techniques used on sea-ice, such as surface surveys (e.g. with theodolites, levels or GPS
receivers) (Strub-Klein and Sudom, 2012), stereophotogrammetry (Divine et al., 2016), lidar (Eicken et al., 2009) and radar ranging, including interferometric synthetic aperture radar (InSAR), have a number of disadvantages such as high costs, long acquisition times, low precision and complexity. For example, several of these techniques are limited to a single measurement per capture cycle per sensor, resulting in linear surveys (e.g. lidar) while others require specific capture conditions and complicated data manipulation (e.g. InSAR).

Structure-from-Motion (SfM) is an emerging low-cost and highly flexible photogrammetry technique that, when combined with a small unmanned vehicle (sUAV) platform and GPS receivers, has been demonstrated as a viable alternative to expensive traditional remote-sensing surveys (Ely et al., 2016). The strength of SfM over classical photogrammetry techniques lies in the bundle adjustment algorithms, where keypoint (unique features identified on multiple images) positions, camera positions, lens calibration models and georeferencing data are iteratively refined to determine a jointly optimal three-dimensional structure for the scene (Smith et al., 2016). This enables the use of consumer camera and computers for accurate surveying (Micheletti et al., 2015). The sea-ice environment presents unique challenges, such as cold weather, non-stationary targets and low-contrast surfaces, which must be overcome to use sUAV-SfM effectively (Dammann et al., 2018). However, sUAV-SfM presents significant advantages relative to the surveying techniques listed above, such as very low capital investment (UAV and instruments) and operation costs, cm-level ground resolution and areal surveying (as opposed to linear surveying).

Previous research successfully used SfM to survey cryospheric features such as snow (e.g., Nolan et al. 2015), icebergs (e.g., Crawford et al. 2018) and glaciers (e.g., Ryan et al. 2015). Sea-ice has also been surveyed with sUAV-SfM (e.g., Eltoft et al., 2015), but no studies were dedicated to the extensive testing of the technique over sea-ice. Consequently, the potential of sUAV-SfM surveys for mapping sea-ice has not yet been fully evaluated.

The aim of this research is to determine the quality of sUAV-SfM topographical surveys of sea-ice, as well as the associated challenges and outcomes of collecting and processing the data at a relatively low cost. The first objective is to quantify the accuracy, precision and repeatability of sUAV-SfM surveys. The second is to employ sUAV-SfM surveys to detect, measure and visualize sea-ice features and changes.

METHODS

Field Methods

Research was conducted on the landfast sea-ice of Frobisher Bay, near Iqaluit, Nunavut (Figure 1a) from May 10-16, 2017. The semi-diurnal tide at the field site had an amplitude of 7-11 m, and generated a non-static landscape with two sea-ice deformation types: a 4 km long pressure ridge with a relatively small prominence of 25 cm (height of the ridge above the surrounding sea-ice surface), and a tide-generated rubble icefield near the shore, where the sea-ice condition alternated between free-floating at high tide and resting on the sea-bed at low tide (Figure 1c).

Multiple SfM surveys and one ground survey were conducted over the course of fieldwork. This paper will focus on a subset of three SfM surveys (SfM surveys 11 to 13) and the ground survey (Table 1). The results from a larger subset of SfM surveys can be viewed in St-Amant (2018).
Table 1.Survey parameters and environmental conditions.

<table>
<thead>
<tr>
<th>Survey name</th>
<th>Date</th>
<th>Altitude (m)</th>
<th>Focal length (mm)</th>
<th>Overlap ratio</th>
<th>Sidelap ratio</th>
<th>Atmospheric conditions</th>
<th>Sea-ice condition</th>
<th>Images captured</th>
<th>Area surveyed (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground survey</td>
<td>10 May</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>66*</td>
<td>50 x 100</td>
</tr>
<tr>
<td>SfM Survey 11</td>
<td>13 May</td>
<td>90</td>
<td>16</td>
<td>0.75</td>
<td>0.75</td>
<td>Variable</td>
<td>Water puddles</td>
<td>92</td>
<td>150 x 500</td>
</tr>
<tr>
<td>SfM Survey 12</td>
<td>13 May</td>
<td>90</td>
<td>16</td>
<td>0.75</td>
<td>0.75</td>
<td>Overcast</td>
<td>Water puddles</td>
<td>92</td>
<td>150 x 500</td>
</tr>
<tr>
<td>SfM Survey 13</td>
<td>13 May</td>
<td>90</td>
<td>16</td>
<td>0.75</td>
<td>0.75</td>
<td>Low light</td>
<td>Water puddles</td>
<td>92</td>
<td>150 x 500</td>
</tr>
</tbody>
</table>

*The number listed here represent the amount of survey points taken of the sea-ice surface.

A Topcon HiPer V L1/L2 GPS receiver located on the bedrock of the nearby shore (hereafter referred to as Land GPS) was used as a Post-Processing Kinematic (PPK) base station. Two additional GPS receivers, a Topcon HiPer V and an Emlid Reach RTK (Ice GPS1 and Ice GPS2, respectively) were positioned on the ice surface to continuously record changes in sea-level. A measured offset from the water surface through an adjacent hole in the ice to each GPS receiver antenna was subtracted from the GPS elevation data for accurate sea-level measurements. These measurements were then used to calculate the elevation of survey points above sea level throughout the study. Four 25 cm x 25 cm markers were placed near the corners of the survey area and were surveyed for use as ground control points (GCPs) (Figure 1b).

A ground survey covering 5000 m² of the study area was conducted on May 10th to provide a topographical reference dataset for accuracy calculations. Ice GPS1 was mounted on a survey pole and points were measured up from the surface (ice or snow). A total of 65 evenly-spaced points were manually recorded over a level section of sea-ice using a Topcon Tesla tablet computer, as well as GCP positions. The elevations of these survey points were adjusted to sea-level using data from Ice GPS2.

UAV Set-Up

The UAV, its payload and the ancillary equipment had an approximate value of CAD $4500 (USD $3400). The payload consisted of a low-cost, L1, carrier-phase recording GPS receiver Emlid Reach RTK (based on the u-blox NEO-M8T; named UAV GPS1 henceforth) and a gimble-mounted Sony a6000 24.3 megapixels digital camera equipped with a Sony E PZ lens with a focal length of 16-50 mm. The payload was mounted on a modified DJI S800 sUAV, controlled by a 3DR Pixhawk autopilot flight controller and dedicated u-blox NEO-M8N L1 GPS receiver (named UAV GPS2 here). Mission Planner software by Ardupilot, version 1.3.50, provided the flight path and shutter activation instructions. The sUAV flew autonomously in a precise ‘lawnmower’ pattern over the survey area until all the planned images were recorded.

The camera settings were chosen manually before each survey to optimize image quality (i.e. high shutter speed, wide aperture and low ISO). During the SfM surveys, the camera shutter was activated at specific distance intervals by the flight controller. The interval was chosen to provide sufficient side and frontal overlap based on the flight path, elevation and camera focal length. The camera shutter trigger timestamp was recorded in the UAV flight controller log file, which also contained the UAV attitude information provided by the autopilot inertial measurement units, and the UAV GPS2 position and time data. A hot shoe adapter on the camera sent a signal to UAV GPS1 at the exact moment the camera shutter was opened, where it was recorded in the form of a timestamp and position.
Figure 1. Overview of the research site and experimental setup. (a) The general position of the research site within Frobisher Bay, marked with a red boundary. (b) A generic site sketch of a SfM survey area. (c) The pressure ridge as it appeared from eye-level. (d) The main components of the sUAV, including the payload (camera and UAV GPS 1).

Data processing

Each GPS file was converted to the RINEX file format using proprietary software from the manufacturers (Topcon Link version 8.2 for the Topcon HiPer V receivers and RTKCONV version 2.4.3 Emlid b28 for the Emlid Reach RTK receivers). The Land GPS RINEX files were post-processed using the Canadian Spatial Reference System Precise Point Positioning (CSRS-PPP) online tool from Natural Resources Canada. The Canadian Geodetic Vertical Datum of 2013 (CGVD2013) was used for elevation. The corrected Land GPS positions were subsequently used as temporary surveying monuments and as base stations for PPK. The remaining RINEX files corresponding to the UAV flights, the ground survey and the ice position were then PPK-processed.

RTKLIB software (version 2.4.2 for Topcon HiPer V files and version 2.4.3 Emlid b28 for Emlid Reach RTK files) used the matching Land GPS RINEX file Precise Point Positioning (PPP)-corrected position for the base station data, and the International GNSS Service highest-accuracy corrected products for satellite ephemerides, earth rotation and atmospheric parameters to refine the positions of UAV GPS1, Ice GPS1 and 2. The resulting geographical coordinates were then projected to the Universal Transverse Mercator (UTM) coordinate system (zone 19N) to simplify subsequent calculations. Elevations were converted from the land-based CGDV2013 datum to a real-time sea-level datum using data from Ice GPS1/2.

The sUAV camera’s optical centre was offset from the antenna phase centre of UAV GPS1 by several cm. This was corrected by accounting for the distance between the two instruments in Cartesian coordinates and the rotation of the sUAV airframe. Attitude data was obtained from the GPS-timestamped UAV log files, recorded every 100 ms and spline-interpolated to 1 ms intervals using a custom R script. Roto-translational offsets were then computed and applied to the position of UAV GPS1 so that it represented camera position. The position of the camera at every shutter trigger event logged by UAV GPS1 was extracted and associated with each image taken during the surveys. These positions were logged to a comma-separated values (CSV) file.
In the raw images captured by the camera, the contrast of the sea-ice surface was poor. This was an anticipated challenge for SfM analysis of sea-ice (Fonstad et al., 2013; Smith et al., 2016; Westoby et al., 2012). As suggested by Nolan et al. (2015), the contrast was increased in the raw image files using the camera-bundled Phase One software (version 10.1.2) by Capture One Express. Gaussian stretches to approximately three standard deviations were manually performed on the image histogram after a white balance was applied. These image modifications were applied identically within each SfM survey, ensuring uniformity between photos. All images were then converted to the JPEG file format.

SfM survey photos, image positions and GCP positions (when available) were processed using Agisoft Photoscan (version 1.3.4) on a high-end desktop computer to derive point clouds and orthophotos. JPEG images were aligned using the ‘highest accuracy’ setting and dense point clouds (named raw point cloud here) were generated using the ‘high accuracy’ setting without depth filtering. Orthophotos were exported with a pixel size of 2 cm.

Raw point clouds generated by Agisoft Photoscan had approximately $8 \times 10^7$ points, which slowed processing and visualization. In addition, high frequency noise in the point positions made the surface boundary appear diffuse (the boundary appeared as a layer of points 5 to 10 cm thick). Raw point cloud decimation and averaging, based on a method proposed by Lague (2015), were conducted using CloudCompare (version 2.9). The Multiscale Model to Model Cloud Compare (M3C2) plugin was used to generate a 'core point' point cloud (named core point cloud here), which reduced the number of points by one to two orders of magnitude and sharpened the estimated sea-ice surface boundary. Core points are uniformly spaced and represent the mean position of all the original points located within a cylinder of a specific diameter and height, which is oriented normal to the point cloud surface of a larger subsampled section of the point cloud. The core point clouds covered an area much larger than the planned surveying area, since Agisoft Photoscan generated points everywhere there was sufficient overlap of images. This area was therefore cropped to the SfM survey boundaries prior to further analysis.

### Accuracy, precision and repeatability metrics

To calculate the accuracy, precision and repeatability of sUAV-SfM surveys of sea-ice, the Cloud-to-Cloud Distance tool from CloudCompare was used to quantify vectors representing the distance and direction between points in a reference point cloud and corresponding points in a compared point cloud. This results in a vector field (i.e. “cloud of vectors”).

Horizontal registration between mostly flat point clouds is difficult (Nolan et al., 2015) and so only the vertical component of the distance vectors ($Z_{\text{dist}}$) was extracted and used in subsequent analyses. This approach is widely used to assess SfM quality (Fonstad et al., 2013; Smith and Damià, 2015) either through point cloud operations or Digital Elevation Models (DEMs). As the $Z_{\text{dist}}$ is a scalar value applied to points in a point cloud, the resulting entity is referred to as a scalar field.

Shapiro-Wilk tests were performed to determine if the $Z_{\text{dist}}$ distributions were normally distributed. The accuracy, precision, and repeatability values were then derived from the $Z_{\text{dist}}$ normal distributions using parametric statistics.

**Accuracy and precision.** To measure the accuracy and precision of sUAV-SfM, the ground survey was used as a reference dataset. The $Z_{\text{dist}}$ between each ground survey point and corresponding SfM core points were calculated. The mean, standard deviation, root mean squared error (RMSE) and the ratio between RMSE and surveying range (altitude above ground) were subsequently calculated for the $Z_{\text{dist}}$ distributions. The theoretical measurement errors from the various instruments were also calculated and evaluated against the $Z_{\text{dist}}$ distributions. These errors were either estimated, in the case of manual measurements, or were provided by the PPP
and PPK files for GPS measurements. Root mean square (RMS) addition was used to account for error propagation between the instruments.

**Repeatability.** To measure repeatability, the rubble ice area was removed from SfM Surveys 11 to 13 (due to significant tidal-induced topographical changes between the surveys). The remaining sea-ice topography was assumed to be unchanged between surveys. The three core point clouds were differenced from each other using the *Cloud-to-Cloud Distance* tool to generate $Z_{\text{dist}}$ scalar fields. The mean, standard deviation, RMSE and RMSE:range were calculated for the $Z_{\text{dist}}$ distribution for each of the three possible survey pairs. In addition, the instrumental errors were measured.

**Mapping sea-ice topography**

Core point clouds were mapped to show elevation and $Z_{\text{dist}}$ scalar values, providing a visualization of the sea-ice topography, shape and texture, as well as topographical changes, and spatial distribution of errors. Orthophotos were used to observe and interpret the sea-ice topography and features, and, when used in conjunction with point clouds, to interpret the point cloud data.

Point cloud-based digital elevation models (DEMs) were checked for artifacts such as surface elevations below sea-level, which provided additional information about the data quality of the core point clouds.

The orthophotos were visually inspected to determine which sea-ice surface features were detectable by the topographic data. Orthophotos were also used to interpret point cloud transects across the rubble ice area. These transects were conducted to visualize the changes in ice topography over time across this area experiencing metre-scale vertical movement due to tides. The elevations were plotted relative to a fixed, land-based vertical datum, instead of the sea-level based vertical datum that was used for the previous analyses.

**RESULTS**

SfM Surveys 11, 12 and 13 yielded a total of 276 images. The three processed SfM surveys represented a total (overlapping) surveyed area of $3.64 \times 10^5$ m$^2$ (prior to cropping), covered by a total of $2.44 \times 10^8$ points (raw point clouds), for an average of 671 points per m$^2$. In all processed surveys, the ridge and rubble field were identifiable topographical features.

**Accuracy and precision**

The $Z_{\text{dist}}$ values between the ground survey and the core point clouds of SfM Surveys 11, 12 and 13 were evaluated with a Shapiro-Wilk test, which determined that for each SfM survey, all values were normally distributed (p-values were 0.59, 0.34 and 0.66, respectively). Parametric statistics were therefore used to calculate the $Z_{\text{dist}}$ accuracy and precision for each SfM survey. The average of the three SfM surveys yielded an accuracy of $56 \pm 14$ mm (95% confidence interval – CI), a precision of 40 mm, a RMSE of 69 mm and a RMSE:range ratio of 1:1265 (Table 2). For the contribution of the instrument sources of errors to the $Z_{\text{dist}}$ RMSE, the RMS additions of these instrument sources of error is 35 mm.
Table 2. \(Z_{\text{dist}}\) statistics between SfM Surveys 11 to 13 and the ground survey.

<table>
<thead>
<tr>
<th>Survey name</th>
<th>Survey 11</th>
<th>Survey 12</th>
<th>Survey 13</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (Z_{\text{dist}}) (m)</td>
<td>0.041</td>
<td>0.066</td>
<td>0.062</td>
<td>0.056</td>
</tr>
<tr>
<td>Standard error of (Z_{\text{dist}}) (m)</td>
<td>0.006</td>
<td>0.009</td>
<td>0.005</td>
<td>0.007</td>
</tr>
<tr>
<td>Standard deviation of (Z_{\text{dist}}) (m)</td>
<td>0.035</td>
<td>0.055</td>
<td>0.029</td>
<td>0.040</td>
</tr>
<tr>
<td>RMSE of (Z_{\text{dist}}) (m)</td>
<td>0.053</td>
<td>0.085</td>
<td>0.069</td>
<td>0.069</td>
</tr>
<tr>
<td>RMSE:range ratio</td>
<td>1:1632</td>
<td>1:1028</td>
<td>1:1275</td>
<td>1:1265</td>
</tr>
</tbody>
</table>

**Repeatability**

The Shapiro-Wilk test values for the \(Z_{\text{dist}}\) distributions of the core point clouds associated with the SfM Survey pairs 11-12, 11-13 and 12-13, using a 600-point sample from each distribution, determined that the distributions were normal with p-values of 0.94, 1.0 and 1.0 for each respective SfM survey pair. The average \(Z_{\text{dist}}\) standard deviation was 77 mm and the RMSE was 80 mm (Table 3). The 95% confidence interval for all the mean values was less than a mm due to the large number of points available (>2 million). The total instrumental error was 40 mm.

Table 3. \(Z_{\text{dist}}\) statistics between SfM survey pairs.

<table>
<thead>
<tr>
<th>SFM Survey pairs</th>
<th>11 vs 12</th>
<th>11 vs 13</th>
<th>12 vs 13</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (Z_{\text{dist}}) (m)</td>
<td>0.016</td>
<td>0.015</td>
<td>0.030</td>
<td>0.020</td>
</tr>
<tr>
<td>Standard error of (Z_{\text{dist}}) (m)</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Standard deviation of (Z_{\text{dist}}) (m)</td>
<td>0.074</td>
<td>0.070</td>
<td>0.087</td>
<td>0.077</td>
</tr>
<tr>
<td>RMSE of (Z_{\text{dist}}) (m)</td>
<td>0.076</td>
<td>0.089</td>
<td>0.076</td>
<td>0.080</td>
</tr>
<tr>
<td>RMSE:range ratio</td>
<td>1:1149</td>
<td>1:986</td>
<td>1:1155</td>
<td>1:1087</td>
</tr>
</tbody>
</table>

**Mapping sea-ice topography**

The elevation maps (i.e. DEM images) for SfM Surveys 11, 12 and 13 display three distinctive topographical features: rubble ice, a pressure ridge and undeformed, level ice (Figure 2). Elevations presented here are relative to the dynamic sea-level, and therefore represents the freeboard elevation. The sea-ice ridge is clearly distinguishable in all point clouds, despite its small width and low prominence above the surrounding level ice. From the elevation maps, there are no indications of topographical changes occurring at the ridge or on level ice while the rubble-ice area displayed metre-scale vertical tidally-induced movement. This ice was assumed to be resting on the sea-floor during SfM Survey 11, partially floating following a rise in sea level of 3.0 m (SfM Survey 12) and fully floating after a further 2.7 m increase in sea level (SfM Survey 13 ) as measured by Ice GPS1/2. This accounts for the between-survey drop in rubble ice elevation relative to the level ice, which was at a constant height above the sea-level datum. The surface texture of the undeformed sea-ice area is observable in Figure 3a, which shows topographical details of small features, such as snowmobile tracks, snow drifts and even the fracture along the ridge’s centreline. In general, the elevation maps do not present significant quality issues, as the point elevations were generally consistent with visual observations made on the ground. There were no noticeable tilts and the relief is representative of what was observed in the field. However, there were some errors, notably in areas where the surface elevation was below sea-level.
The visual inspection of the orthophotos revealed that other ice features were detectable with the point cloud elevation maps in addition to the topographical features. Melt ponds, fractures and snow were all easily identifiable from the orthoimage (Figure 3b). Transects of point clouds across the rubble ice area and the related orthophotos (Figure 4) provided information about the ice dynamics in the intertidal zone and illustrated how the tides and sea-floor influenced the sea-ice topography. Alignment of elevations along sections of the transect (Survey 11 and 12 between approximately 25 and 70 m on the horizontal axis of Figure 4e), indicates an absence of tide-induced movement during the inter-survey period. In contrast, the discrepancy between SfM Survey 13 and the other surveys indicates that all the ice across the transect was floating to some degree. This interpretation is supported by the orthophotos. Although some of the changes between the orthophotos were due to variability in lighting conditions, the effects of the rising tide on the sea-ice is clearly discernible: the ice became progressively flatter, water ponds gradually appeared, and the width of ice fractures changed.

Figure 3. (a) An elevation map close-up and (b) an orthophoto from SfM Survey 11.
DISCUSSION

Accuracy and precision

Published values for typical SfM RMSE:range ratios are between 1:625 and 1:1000 (Eltner et al., 2016; Smith et al., 2016). This corresponds to an RMSE of 87 to 140 mm at the altitude flown during this study, which is close to the mean accuracy value of 69 mm obtained herein. SfM Surveys conducted on May 10th, the same day of the ground survey, were initially designed to assess SfM accuracy and precision. These surveys had overlapping areas however, due to GPS data quality issues with the SfM surveys on that day, SfM Surveys 11-13 on May 13th were used instead. Since SfM surveys 11-13 surveyed areas did not match that of the ground survey, only 4% of the area of SfM surveys 11-13 overlapped with the ground survey, thus lowering the representativeness of the results.

The mean RMSE value of 69 mm was, however, representative of the immediate area surrounding the ground survey for SfM Surveys 11, 12 and 13. With a mean RMSE:range ratio of 1:1265, this specific section of SfM Surveys 11, 12 and 13 outperformed the commonly cited RMSE:range ratios (Eltner et al., 2016; Smith et al., 2016) by an impressive 27% to 102%. A more conservative RMSE:range ratio of 1:1000, might be representative of the accuracy of sUAV-SfM surveys of sea-ice in general, as this ratio is known to be achievable by SfM according to published results. This RMSE:range ratio represents a RMSE value of approximately 87 mm at the flight altitude in this study. These conservative adjustments would better consider the presence of SfM Survey points with an elevation below sea-level, as observed in Figure 2.
Repeatability

The repeatability error measures (RMSE of 80 mm and RMSE:range ratio of 1:1087) have a more constrained confidence interval than both the accuracy and precision results. This is primarily due to the number of points compared (>2 million vs. 65) and percentage of overlap between point clouds (100% between SfM surveys vs. 4% between SfM surveys and the ground survey).

Mapping sea-ice topography

The elevation map (Figure 3a) demonstrated the ability of SfM to represent fine topographical details of the sea-ice such as snow drifts, snowmobile tracks and shallow ridges. Overall, the local topography was representative of the sea-ice topography observed in the field.

The orthophotos provided useful information about the ice topography and surface cover such as ice, snow and water (Figure 3b) and enhanced the interpretation and identification of the topographical features observed in the point clouds. They also enabled the identification of detailed features that would have been difficult to find with point cloud data alone, such as the cm-level width fractures that ran along the crest of the ridge.

The transect graph enabled the visualisation of the intertidal zone sea-ice topographic changes across multiple SfM surveys (Figure 4). The interaction between the sea-ice, sea-floor and ocean was clearly discernible while the tide was changing. The location of the hinge point, ponds and ice blocks could all be determined from the transects and the high density of the point cloud enabled fine-scale topographical details to be observed.

Overall, the maps, orthophotos and transects provided valuable information about the sea-ice topography and detection of topographical changes associated with the tidal cycle.

Practical applications

The main advantage of sUAV-SfM is the ability to generate dense point clouds and orthophotos at low costs over small spatial scales. It has the potential to become a surveying technique of choice, particularly for pressure ridge surveys, as the spatial scale of pressure ridges along their thinnest dimension is generally small when compared with the resolving power of many surveying techniques (Strub-Klein and Sudom, 2012).

Ridge surveying most commonly involves labour intensive ground surveys or drilling techniques and may be more efficiently conducted using sUAV-SfM techniques. The results of this study clearly demonstrate that sUAV-SfM surveys can easily resolve even low prominence ridges. Therefore, no issues are expected from the surveying of ridges of greater elevation by sUAV-SfM, which are common (e.g. Strub-Klein and Sudom’s (2012) review of over 300 first-year pressure ridges found that the mean sail dimensions of pressure ridges were 2 m height by 12 m width). Ridge dimensions, including submerged features that can be estimated from the sail dimensions (Strub-Klein and Sudom, 2012), are essential ice measurements required for engineering, navigation, modelling and space-borne remote sensing of sea-ice. For engineering purposes, ridge dimensions are required to estimate the maximum force they can exert on structures. For navigation, the same principles apply to route-finding as stronger ridges require more effort and time to be breached by icebreakers. Furthermore, for ice-surface transport, steep and rugged ridges can be perilous obstacles for foot and vehicle travel (Dammann et al., 2018). Finally, there is a need for field measurements of the ridging process for the development and validation of sea-ice models.
sUAV-SfM may also be used to estimate the local sea-ice thickness for Arctic ports or icebreaker operators. It can also validate ice thickness estimates from instruments operating at a larger spatial scale (lidar and radar) or for measuring snow distribution patterns on sea-ice, surface melt monitoring, lead measurements and security surveillance, etc.

CONCLUSIONS

This study has demonstrated that sea-ice topography can be surveyed by sUAV-SfM with excellent accuracy, precision, repeatability and spatial resolution at the km-level spatial scale. It can therefore be concluded that sUAV-SfM is a viable low-cost sea-ice topography mapping technique. However, reliability, particularly with respect to low-cost GPS receivers and guaranteeing appropriate flying conditions, remains a challenge.

This study provided the first known extensive testing of sUAV-SfM for topographical surveys of sea-ice. The difficulties associated with conducting sUAV-SfM surveys of sea-ice were demonstrated to be surmountable. The overall capabilities are now better defined, and the technique has proven to be valuable despite its low-cost. These results have a strong potential to be of interest to prospective sUAV-SfM users, from sea-ice scientists and engineers, to local government in Arctic communities and icebreaker operators.

ACKNOWLEDGEMENTS

We would like to thank Ted Irniq, Jamal Shirley and Rick Armstrong of the Nunavut Research Institute for field assistance. The Northern Scientific Training Program, Natural Sciences and Engineering Council of Canada, ArcticNet, a Network of Centres of Excellence of Canada, Canadian Armed Forces and Mapping and Charting Establishment, Canada Foundation for Innovation and Ontario Research Fund provided equipment, logistics and financial support. We thank Anna Crawford for insightful suggestions on data processing and analysis techniques and Nick Brown for comments on an earlier version of the manuscript.

REFERENCES


St-Amant, M., 2018. *Sea-ice topographic surveying using Structure-from-Motion photogrammetry conducted from small UAVs*, MSc Thesis, Department of Geography and Environmental Studies, Carleton University, Ottawa, Canada.

