RESEARCH ARTICLE

UAV-Based Survey of Glaciers in Himalayas: Challenges and Recommendations

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Abstract
Role of Unmanned Aerial Vehicle (UAV)-based remote sensing (RS) applications in glaciology have increased in recent years. UAV-based RS studies on mountain glaciers are mainly focusing on obtaining accurate ultra-high-resolution data from UAV images for different glaciological applications. However, studies understanding the challenges involved during UAV surveys on complex terrains of high mountain glaciers are inadequate and they are not available for places like Himalayas. Therefore, this study aims to examine and derive strategies to minimize those challenges on such complex glacier and their margin topography. Here, UAV surveys were conducted using a fixed-wing commercial-grade off-the-shelf UAV (eBee series, SenseFly) on three glacier sites (East Rathong, Hamtah and Panchinala-A) located in different climate regimes within the Indian part of Himalayas. From the UAV collected images, ultra-high-resolution ortho-mosaicked images and Digital Elevation Models were generated at 0.1 m ground sample distance and their accuracies were assessed using the collected ground control points. Based on the challenges observed, the study recommends criteria for selection of best-suited take-off/landing locations on a mountain glacier and its margins for conducting efficient UAV surveys in the complex terrain such as in the Himalayas and possibly beyond. Recommendations reported in this article shall be useful to minimize the challenges and associated risks during UAV data acquisition using fixed-wing UAVs.

Keywords Digital elevation models • Ortho-mosaicked images • Glacier • Remote sensing • Unmanned aerial vehicle

Introduction

Glaciers are perennial features that temporarily store freshwater as a thick mass of crystalline ice and snow on the land. Globally, mountain glaciers are losing ice mass in the early twenty-first century twice that of the end of the previous century (Maurer et al. 2019). In such a scenario, continuous monitoring of glaciers at local and regional levels is essential. On a global scale, numerous efforts are being made to observe and monitor glacier health using ground-based, aerial and spaceborne remote sensing platforms (e.g. Strozzi et al. 2004; Haeberli et al. 2007; Vincent et al. 2012; Wang et al. 2014; Bhardwaj et al. 2015; Yordanov et al. 2019).

Despite such efforts, only sparse and limited data from ground-based observations are available for reference or validation purposes (Zemp et al. 2017). Notably, the Himalayan region in Southwest Asia has significant gaps in ground-based observations (Stumm et al. 2017; Zemp et al. 2017). Remoteness and rugged terrains restrict ground-based observations, which are time-consuming and logistically challenging (Bajracharya et al. 2014). Though aerial surveys can cover glaciers at a regional scale at required place and time, harsh weather conditions on high altitudes raise safety concerns. Moreover, repetitive aerial surveys are not feasible for glaciological studies due to high costs. Likewise, existing spaceborne remote sensing platforms have many limitations for collecting individual glacier level accurate data at high resolutions despite having...
numerous advantages for global-scale glacier monitoring (Bhardwaj et al. 2015). At this juncture, Unmanned Aerial Vehicles (UAV) as a remote sensing platform, which can fly below the clouds and easily portable, has enormous potential to augment the sparse and discontinuous field observations by providing ultra-high-resolution images at relatively low costs.

The technological advances in sensors with navigation modules have increased the potential of UAV as a platform for remote sensing (Pajares 2015). This potential has led to new facets in acquiring UAV-based remote sensing data such as the ability to acquire ultra-high-resolution, availability of comprehensive spectral and geometric data, and fusion of multi-sensor data (Yao et al. 2019). Especially, the remarkable development of UAVs with onboard Global Navigation Satellite System/Global Positioning System (GNSS/GPS) receiver; Inertial Measurement Unit (IMU); high endurance capabilities, and 3D model generation by Structure-from-Motion (SfM) process has paved excellent opportunities for deploying UAV-based RS platform in glacier studies (Bhardwaj et al. 2016a, b). Platforms like Terrestrial and Airborne Light Detection and Ranging (LiDAR) are also equally reliable for glacier studies due to their data accuracy (Bhardwaj et al. 2016a, b). However, in glaciological studies UAV-SfM gained more popularity because of its low cost and less complexity in processing data than Aerial LiDAR (Bash et al. 2020). Moreover, UAV-SfM-based photogrammetry enables higher coverage with simple logistics compared to UAV-based LiDAR (Fugazza et al. 2018).

Although the UAV-based RS technology is gaining popularity among researchers, certain hurdles such as limited accessibility of mountain glaciers and the challenges related to flying in high altitudes due to rugged terrains are hindering the progress of UAVs in glacier research, especially in high mountain regions such as the Himalayas. This is evident from the geographical distribution of available studies, where most of the UAV-based glaciology applications are focussed on polar and sub-polar regions (Antarctica, Greenland and Norway), followed by mountain glacier regions of Canada, the Alps and at last the Himalayas (Gaffey and Bhardwaj 2020).

Despite such challenges, in recent years the application of UAVs in high mountain regions worldwide is gaining momentum although still comparatively lower than the Polar and Sub-polar regions (Buri et al. 2016; Kraaijenbrink et al. 2016a; Wigmore and Mark 2017; Mark et al. 2017; Bodin et al. 2018; Fugazza et al. 2018; Kaufmann et al. 2018; Vivero and Lambiel 2019). Within mountainous regions, studies demonstrating the UAV applications in Himalayan glaciers remain sparse. Apart from the current study, till date, UAV-based RS applications in Himalayas are explored in the field of permafrost at Kunlun mountains, China (Luo et al. 2018); snow studies on Tibetan plateau, China (Liang et al. 2017); and glaciology studies in Lirung, Changri Nup, Lantang and Thulagi glaciers in Nepal (Immerzeel et al. 2014; Vincent et al. 2016; Kraaijenbrink et al. 2016a, b, 2018; Brun et al. 2018; Watson et al. 2020). Reasons behind the lesser number of UAV-based studies on Himalayan glaciers could be because the terrain is hostile, highly debris-covered, located at high altitudes (the average elevation of the Himalayas is significantly higher than the Alps and the Andes mountain ranges) making logistics and movements much more difficult. Moreover, applying UAV photogrammetry to the Himalayan glaciers poses additional challenges such as low air pressure, poor GNSS receptions for UAVs with automatic navigations. Apart from these, restrictions for operating UAVs in Himalayan countries are also to be noted.

As stated in Groos et al. (2019), except few (e.g. Ryan et al. 2015; Jouvet et al. 2019), most of the glaciological studies use Commercial off-the-shelf (COTS) UAVs to acquire aerial images in a high spatial resolution (e.g. Vivero and Lambiel 2019; Fugazza et al. 2015; Rossini et al. 2018). The benefit of commercial UAVs is obvious: they are reliable and ready-to-use and have shown higher usage rate (Gaffey and Bhardwaj 2020). It is also observed that most of the UAV-based glaciological studies (e.g. Immerzeel et al. 2014, Ryan et al. 2015; Gindraux et al. 2017; Jouvet et al. 2019; Chudley et al. 2019) use fixed-wing UAVs rather than rotary-wing UAVs. This is mainly due to the advantages of fixed-wing UAVs in providing better aerodynamics, longer flight duration, cover larger area per flight and fly higher than rotary-wing (Bhardwaj et al. 2016a, b). Also, multirotor, i.e. rotary-wing platforms could show flight instabilities and distorted images at high mountainous regions due to low air pressure (Gaffey and Bhardwaj 2020). However, great care is required in identifying proper take-off and landing sites in rugged mountainous terrain to prevent physical damages to the fixed-wing UAVs.

On the other hand, to obtain accurate glacier topography, UAV-based SfM methods rely on Ground Control Points (GCPs). A recent study by Gindraux et al. (2017) reported that on all seasons 17(7) GCPs per km² are adequate for achieving centimetre level vertical (horizontal) accuracy in Digital Surface Model (DSM) because further increase in GCP points showed very less improvement in their accuracy. Their study was able to achieve vertical (horizontal) accuracy of range 0.1–0.25 m (0.03–0.09 m). Following this, other glacier studies have also used GCPs (varying between seven and seventeen) to generate DEMs at centimetre and decimetre level accuracies (e.g. Wigmore and Mark 2017; Rossini et al. 2018; Groos et al. 2019). However, the topography of most of the Himalayan...
glaciers are complex where even collecting desired GCPs are impractical due to safety reasons.

Despite the increasing use of UAVs in glaciology, studies on how the terrain characteristics of a glacier and their margins will affect the full potential of UAV flights remain less explored. Therefore, studies addressing the practical challenges of UAV surveys in inaccessible terrain and harsh meteorological conditions like the Himalayas are indeed essential, where such studies are not yet conducted and reported. Towards filling this gap, this article collates the authors’ experiences gained from UAV-based surveys carried out at glaciers located in different river basins in Indian Himalayas. This study used COTS fixed-wing UAV (Sensefly eBee series) mounted with a digital RGB camera to acquire images on the ablation regions of the study glaciers. The study aims to,

- Examine the challenges faced during UAV surveys of glaciers and their impacts on the UAV data products.
- Provide potential strategies and suggestions to identify take-off/landing locations for conducting efficient UAV surveys using fixed-wing UAVs.

**Data and Methods**

**Study Area**

UAV surveys were conducted on three glaciers, namely East Rathong, Hamtah and Panchinala-A in the Indian Himalayan region. The location, areal extent, elevation and debris cover details of these glaciers are given in Table 1. Though the chosen glaciers share nearly similar lengths and hypsometry, they vary from one another with respect to different terrains surrounding the study glacier margins. Figure 1a shows the locations of the study glaciers and the area covered by the UAV surveys.

**Table 1** Details of the study Area(s)

| Glacier     | Location       | Areal extent (km²) | Mean elevation (~ m a.s.l.) | Length (km) | Basin (Region)          |
|-------------|----------------|--------------------|----------------------------|-------------|-------------------------|
|             | Latitude       | Longitude          | Total (Debris cover)       |             |                         |
| East Rathong| 27° 34’ N to 27° 37’ N | 88° 06’ E to 88° 08’ E | 6.06 (0.91) | 5760       | Teesta basin (Eastern Himalayas) |
| Hamtah      | 32° 12’ N to 32° 18’ N | 77° 18’ E to 77° 24’ E | 3.24 (2.37) | 4688       | Chandra Basin (Western Himalayas) |
| Panchinala-A| 32° 41’ N to 32° 44’ N | 77° 17’ E to 77° 19’ E | 4.11 (1.19) | 4930       | Bhaga Basin (Western Himalayas) |

East Rathong is a South-East facing summer nourished valley glacier (Racoviteanu et al. 2014), and it is the only benchmark glacier in the Eastern Indian Himalayan region (Fig. 1d), which is being monitored regularly from 2013 (DST and Climate Change, Government of Sikkim). This glacier is covered by debris, i.e. 15% of total glacier area and surrounded by steep lateral walls at the lower ablation regions. It originates at ~ 6800 m above sea level (a.s.l.) and terminates at ~ 4720 m a.s.l.

Hamtah glacier is a North facing valley glacier fed by the mid-latitude westerlies (Fig. 1c). This glacier is one of the benchmark glaciers in Western Indian Himalayas being monitored since the early 2000s (Azam et al. 2018). This glacier is mostly covered by debris, i.e. 73% of total glacier area and surrounded by steep lateral and headwalls. The glacier is ~ 6 km long with an average width of 0.5 km and lies within the elevation range of 4000–5000 m a.s.l.

Following SAC, ISRO (2016) report, the glacier in Fig. 1b is named as Panchinala-A. The Panchinala-A glacier is North facing valley glacier which also lies in the Western Indian Himalayan region nourished by mid-latitude westerlies. The glacier is covered by debris, i.e. 29% of total glacier area and has fewer steep walls than that of the other study glaciers. The glacier is ~ 5 km long with an average width of ~ 0.55 km and lies within the elevation range of 4300–5990 m a.s.l.

**Methods**

The study consists of three stages: (i) data acquisition, (ii) data processing, and (iii) preparation of data products. Figure 2 illustrates the methods adopted in these three stages. First, data acquisition activities by UAV and the Differential Global Navigation Satellite System (D-GNSS) surveys for GCPs collection are discussed for all the three study glaciers. The field photographs taken on surveyed sites are shown in Fig. 3. Figure 3a–c shows the captured terrain at snout region of East Rathong, Hamtah and...
Panchinala-A glaciers, respectively. Following data acquisition, post-processing of the collected UAV photographs and GCPs is discussed. Finally, the observations inferred from the UAV extracted data products such as Ortho-mosaicked images, DEMs and their slope characteristics are reported and discussed.

D-GNSS Survey

Before each UAV survey, the D-GNSS survey was conducted on all three study glaciers and nearby sites to georeference and validate the ortho-mosaicked images and DEMs (Table 2). Based on the available GCP collection strategies, the study used the most preferable approach for high positional accuracy, i.e. GCPs measured with D-GNSS. The D-GNSS setup used here includes one rover and base station (Trimble Zephyr antennas) with two handheld controllers (GeoExplorer GeoXH). GCPs were collected on identifiable natural targets like boulders at Hamtah (c) and Panchinala-A (b) with the boundaries of UAV surveyed area (violet). Background image source of glaciers: Hillshade of ALOS World 3D—30 m (AW3D30) Version 3.1

UAV Flight Plan Design and Survey

To conduct the UAV surveys, a commercial-grade off-the-shelf fixed-wing UAV (eBee series, SenseFly) was used. This UAV has a central body, detachable fixed wings and a propeller at the tail. It is equipped with an onboard GNSS
and Inertial Measurement Unit (IMU) modules. The hardware component, including battery and RGB camera module, weighs approximately 1.2 kg. Two-modes of GNSS acquisition are possible in this UAV, i.e. standalone, and RTK mode. Here, the UAV surveys were carried out in standalone mode because of the lack of RTK license. The camera module of the UAV was equipped with Sony DSC-WX220 (for East Rathong and Hamtah glaciers) and SenseFly’s Sensor Optimized for Drone Applications (S.O.D.A.) (for Panchinala-A glacier) RGB cameras. The SODA camera is the first sensor, explicitly built for professional drone photogrammetry. Among these two RGB sensors, S.O.D.A. has relatively larger swath width and resolution, which was launched by Sensefly with dedicated features for UAV photogrammetry. The adopted UAV setups and their specifications, along with the details of the software used for flight planning and data processing, are given in Table 3.

The UAV survey flight missions were planned and executed with the eMotion version 3 software package. Figure 3f, g shows the senseFly eBee plus fixed-wing UAV setup and take-off at one of the study sites, i.e. Hamtah glacier. The communication was established between the flight management software and the UAV via a radio frequency (RF) modem. The setup, i.e. laptop with flight management software (eMotion v3) and RF modem, tends to act as ground control station (GCS). With the eMotion software, flight plans were generated as mission blocks with the flight parameters (such as ceiling height, the radius of UAV coverage area, UAV take-off and landing and mission block generation) and SRTM DEM of a given terrain. All the flight missions were pre-set and automated within eMotion software. Table 4 shows the data acquisition characteristics of the adopted UAV mission plan for the selected glacier sites. It shall be noted that, in the study sites wind speeds generally increase over the course of the day and therefore, all UAV flights were performed in the morning (before 11 am) to maximize flight stability and image quality. The average wind speed was observed to vary between 4 and 6 ms$^{-1}$ at the time of UAV flights in all the surveyed sites (Table 4). At East Rathong, UAV survey was conducted in two locations, viz, (i) on ablation region of the glacier (hereafter referred as ER1) and (ii) below the glacier terminus, i.e. stable ground on 2 October.
2017 (hereafter referred as ER2) (Fig. 4a). Whereas, at Hamtah (Fig. 4b) and Panchinala-A (Fig. 4c) sites, UAV surveys were conducted at the lower portion of the glaciers covering some part of ablation area and stable ground surface. The areal extents and photograph locations captured by UAV, location of GCPs, checkpoints, D-GNSS base station locations and UAV take-off point at East Rathong, Hamtah and Panchinala-A glaciers are also shown in Fig. 4a–c, respectively.

UAV Ortho-Mosaicked Images and DEM Extraction

From the acquired UAV geotagged images, data products such as ortho-mosaicked images and DEMs were generated using the Pix4D Mapper software version 4.4.9, which uses the Structure for Motion (SfM) technique. As there were no trees, grass, or any other features present above the surface, UAV-derived DSM is considered as DEM throughout this study. The Pix4D mapper processed the photographs in three stages: initial processing, generation of point cloud and mesh and finally ortho-mosaicked image and DEM generation. The UAV collected photographs were referenced with WGS84 (EGM 96 Geoid) datum, and the output coordinate system was set as WGS 84, UTM Zone 43 N for the Hamtah and the Panchinala-A glaciers and WGS84, UTM Zone 45 N for the East Rathong glacier.

In the initial stage of UAV data processing, the image scale size was set to the UAV acquired image scale. Then, key point extraction was set to an automatic mode where the images are matched to compute key points, and then automatic tie points are built and analysed. Following this, standard calibration mode was set to optimize the camera parameters.

To improve accuracy, the georeferencing process was carried out by accurately identifying the central points of
the collected GCPs targets on three surveyed sites. Following Rossini et al. (2018), amongst the collected GCPs (lying within the UAV surveyed site) two-third of them were used for georeferencing and one-third for validation. In East Rathong site, out of 6 GCPs, 5 GCPs were collected at ER2 and one GCP at ER1. Due to insufficient GCPs at ER1, georeferencing and validation were not possible. However, at ER2 the georeferencing was done with all 5 collected GCPs sparing none for validation. It is because the GCPs were confined in a small area and hence, validating in such scenarios is not appropriate. At Hamtah site, out of 5 GCPs, 3(2) GCPs were used for georeferencing (validation). Likewise, in Panchinala-A, out of 9 GCPs, 6(3) GCPs were used for georeferencing (validation).

In the next stage to generate the dense point cloud and mesh, image scale size was set to half of the image size and default optimal level option was set to create dense point clouds. From the generated dense point cloud and mesh, ortho-mosaicked images and DEMs were reconstructed. Apart from georeferencing and validation with GCPs, the same procedure was followed to generated ortho-mosaicked images and DEMs for all the three glacier sites.

Results

At East Rathong site, with two flights, the fixed-wing UAV (eBee plus) was able to cover 0.78 km² area in ~ 21 min in ER1 and 0.29 km² area in ~ 6 min in ER2 at an average altitude of ~ 215 ± 3 m above the ground level. Whereas, on Hamtah site, a single flight by the UAV covered 0.75 km² area in ~ 45 min at an average altitude of ~ 140 ± 6 m above the ground level; at Panchinala-A site, a single flight by the UAV covered 1.38 km² area in ~ 30 min at an average altitude ~ 170 ± 12 m above the ground level. The surveyed sites include both glacier and adjacent non-glacier regions. Among these, UAV covered 12.80%, 15.70% and 13.86% of the total glacier area in East Rathong, Hamtah and Panchinala-A glaciers, respectively. For all three surveyed sites, UAV collected images were acquired at different GSDs, and then ortho-mosaicked images and DEMs were generated with 10 cm/pixel GSD. The UAV coverage area and their flight-related attributes for the selected three glacier sites are shown in Table 5.
For accuracy assessment of the UAV generated DEMs, GCPs collected during the D-GNSS survey were used. The D-GNSS survey collected six GCPs on the East Rathong region in ER1 and ER2, fifteen GCPs on the Hamtah and nine GCPs on the Panchinala-A sites (see Table 2). The collected GCPs were then post-processed using Trimble Path Finder Office software package. The positional accuracy of the base corrected 6 GCPs in the East Rathong region has 96% of the sample points ranged within 5–15 cm. For 15 GCPs in Hamtah region, 82% of sample points ranged within 5–50 cm and remaining 18% are above 50 cm because at that time of acquiring GCPs there were only a few satellites due to the steep walls surrounding the glacier. For 9 GCPs in Panchinala-A region, 95% of sample points ranged within 5–15 cm.

**Accuracy of UAV-Derived DEMs**

To ascertain the effects of GCPs on UAV data products accuracy, UAV-derived DEMs were generated with and without GCPs for all the three surveyed sites. Care was taken that D-GNSS collected GCPs and UAV-derived

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**Table 3** Ground survey list of GCPs with elevation, date and time of D-GNSS data collection

| Study Glaciers | D-GNSS survey details | Total GCPs collected (GCPs within the UAV surveyed area) | Number of Check Points (CP) used |
|---------------|-----------------------|--------------------------------------------------------|---------------------------------|
| East Rathong  | Date 02-10-2017       | Elevation (m)                                           |                                 |
|               | 4657.833 4627.535     | 06:46:20 am to 03:13:00 pm (8 h 45 min)                 | 6 (-)                           |
|               | 4618.103 4611.077     |                                                        |                                 |
|               | 4613.334 4605.301     |                                                        |                                 |
| Hamtah        | Date 20-09-2018       | Elevation (m)                                           |                                 |
|               | 4012.274 4010.142     | 1:51:08 pm to 03:48:27 pm (2 h)                         | 15(3)                           |
|               | 4010.105 4014.639     |                                                        |                                 |
|               | 4084.995             |                                                        |                                 |
|               | 4135.590 4196.704     | 06:30:04 am to 03:00:00 pm (8 h 30 min)                 | 9(6)                            |
|               | 4217.000 4260.980     |                                                        |                                 |
|               | 4314.276 4325.920     |                                                        |                                 |
|               | 3983.737 3976.487     |                                                        |                                 |
|               | 3979.729 3953.747     |                                                        | 3                               |
|               | 3954.330             |                                                        |                                 |
| Panchinala-A  | Date 14-06-2019       | Elevation (m)                                           |                                 |
|               | 4324.793 4315.976     | 06:17:11 am to 12:52:34 pm (6 h 35 min)                 |                                 |
|               | 4299.974 4259.891     |                                                        |                                 |
|               | 4215.826 4206.834     |                                                        |                                 |
|               | 4195.622 4204.626     |                                                        |                                 |
|               | 4216.628             |                                                        |                                 |
Table 4 Data acquisition details of the UAV survey carried out in the study glaciers

| UAV data acquisition details | East Rathong | Hamtah | Panchimala-A |
|-----------------------------|--------------|--------|--------------|
| Survey dates                | 2 & 3 October 2017 | 20 October 2018 | 14 June 2019 |
| Camera Focal length (mm)    | 4            | 4      | 11           |
| Aperture                    | f/3.3–8      | f/3.3  | f/9–11       |
| Resolution (Megapixels)     | 18.2         | 18.2   | 20           |
| Distance between photographs (m) | 36           | 36     | 36           |
| Distance between flight line (m) | 78           | 78     | 66           |
| Single image swath (m)      | 196 × 144    | 196 × 144 | 219 × 146    |
| Overlap: Side × Frontal (m) | 60 × 75      | 60 × 75 | 70 × 75      |
| Observed average wind speed (ms$^{-1}$) during flight | ~ 5          | ~ 4    | ~ 6          |
| Mode of landing             | Linear       | Linear | Linear       |

DEM were at the same coordinate system. In the case of East Rathong (for ER2 site), DEM generated without GCPs shows a vertical root mean square error (RMSE) of 31.83 m and horizontal RMSE of 1.74 m (Table 6). In the case of Hamtah glacier, DEM generated without GCPs shows a vertical RMSE of 21.52 m and horizontal RMSE of 4.29 m. Whereas, in Panchimala-A site, the DEM generated without GCPs shows vertical RMSE of 0.63 m and horizontal RMSE of 2.88 m, which is lower than the other two surveyed sites. Higher errors in UAV-derived DEMs (without GCPs) at ER2 and Hamtah sites could be due to (i) instability of the flying UAV because of air turbulence and (ii) the presence of steep glacier valleys which obstructed the GNSS satellite signals. However, at Panchimala-A site, vertical error in the DEM (without
GCPs) is comparatively lower than that of ER2 and Hamtah sites but not the horizontal error (Table 6).

As mentioned in Sect. 2.2.1, collecting adequate GCPs as recommended by Gindraux et al. (2017) was not possible due to safety concerns posed by hostile terrain. Nevertheless, georeferencing the DEMs was done with available GCPs on three glacier sites. Obtained results indicate that a significant improvement in horizontal and vertical accuracies is observed at ER2 and Hamtah sites than the DEMs generated without GCPs (Table 6). However, for Panchinala-A, error in the generated DEM (without GCPs) was already less and hence, only minor improvement is observed in the DEMs (with GCPs). Finally, when these georeferenced DEMs were validated with available checkpoints (CPs), the results show that the vertical (horizontal) accuracy of the derived DEM is 0.45 m (0.15 m) at Hamtah site and 0.21 m (0.10 m) at Panchinala-A site. For East Rathong sites (ER1 and ER2), the collected GCPs were insufficient, i.e. no CPs, hence, validation was not done. For example, at ER1, only one GCP was available and at ER2, it is uneven distribution of GCPs, i.e. GCPs confined to only a small portion of the survey area (Fig. (4a)) at ER2 sites.

Analysis indicates that the target type (stable natural feature/artificial targets) used for collecting GCPs also influences the DEM accuracy to some extent. In Table 5, the vertical error of GCP corrected DEM at ER2 was 1.49 m, which is comparatively higher than that of vertical errors of Hamtah and Panchinala-A DEMs. This is because at ER2 the GCPs were collected on stable natural features and identifying the central point on natural targets while generating the DEM are less obvious as discussed by Ewertowski et al. (2019). Whereas, at Hamtah and Panchinala-A sites, GCPs were collected on artificial targets and was able to accurately locate central points on their targets while generating DEMs (see Sect. 2.2.3.). For illustration, Fig. 4 shows the visible natural GCP target (Fig. 4a) and artificial GCP targets (Figs. 4b, c) on the three study glacier sites. Further detailed analysis of the DEM accuracies got hampered due to different flying heights of the UAV flights and different sensors used for DEM generation. Therefore, studies that aim to accomplish DEM accuracy assessment should be careful to collect adequate and well distributed GCPs as mentioned by Tonkin and Midgley (2016) and Gindraux et al. (2017) and fly UAVs with same sensors at similar flying heights by following appropriate flying guidelines.

### Table 5 Details of UAV coverage area and flight-related information of the three glacier sites viz., East Rathong, Hamtah and Panchinala-A

| Attribute | East Rathong | Hamtah | Panchinala-A |
|-----------|--------------|--------|--------------|
| Total Glacier area (UAV surveyed area) (km²) | 6.06 (1.07) | 3.24 (0.75) | 4.11 (1.38) |
| Glacier area covered by UAV (km²) | 0.78 | 0.51 | 0.57 |
| No of Photographs captured | 135 | 107 | 360 |
| Total number of flights to cover the surveyed area | 4 | 3 | 1 |

### Table 6 Root Mean Square Error (RMSE) of DEMs generated from Pix4D without GCPs, with GCPs and from the checkpoints on East Rathong (ER2), Hamtah and Panchinala-A sites.

| Glacier name (ER2) | Without GCP(s) | With GCPs | With checkpoints (during validation) |
|--------------------|----------------|-----------|--------------------------------------|
|                     | $R_{xy}$ (m) | $R_{z}$ (m) | $R_{xy}$ (m) | $R_{z}$ (m) | $R_{xy}$ (m) | $R_{z}$ (m) |
| East Rathong        | 1.74          | 31.83      | 0.04       | 1.49       | –          | –          |
| Hamtah              | 4.29          | 21.52      | 0.04       | 0.06       | 0.15       | 0.45       |
| Panchinala-A        | 2.88          | 0.63       | 0.03       | 0.08       | 0.10       | 0.21       |

$R_{xy}$, $R_{z}$ denotes RMSE of horizontal ($x$ and $y$) and vertical ($z$) surface, respectively.

$\text{UAV surveyed area includes glacier and non-glacier regions; } AED—\text{Used SRTM elevation data (WGS84 horizontal datum and the EGM96 vertical datum).}$
Glacier Topography Maps

For the UAV surveyed area at three study sites, DEMs and their respective slope maps were generated. Topographic map of the surveyed area of the East Rathong glacier site at ER1 shows that surface elevation ranges from 4619 m a.s.l to 4803 m a.s.l with an average slope of 15.30° (Fig. 5a). At ER2, which is on the stable ground located below the glacier terminus region, the surface elevation ranges from 4573 m a.s.l to 4673 m a.s.l with an average slope of 16.24° (Fig. 5b). In Hamtah glacier site, surface elevation ranges from 3988 m a.s.l to 4236 m a.s.l with an average slope of 21.30° (Fig. 5c). Here, ice-cliffs were observed to have steeper slopes and dominant at the left region and glacier snout region. The Panchinala-A glacier (Fig. 5d) DEM and slope maps show that the elevation ranges from 4163 m a.s.l to 4489 m a.s.l with an average slope of 21.73°. From the generated slope maps, it is observed that the ablation region of the Panchinala-A and the Hamtah glacier terrains is more undulated than the East Rathong glacier.

Discussions

Challenges Faced During the UAV Data Acquisition

The difficulties experienced during UAV data acquisition over the three glacier sites are studied and discussed here.

East Rathong During the UAV survey, the UAV’s GNSS module was able to receive fewer satellite signals
(3–4 satellites) throughout the survey because of the obstructions from steep walls surrounding the glacier. Moreover, low air density made the UAV to land faster than the average speed. As a result, UAV landed 20-30 m away from the assigned location, which caused damages like cracks on the central body and edges of fixed wings and hence, we had to abort the further planned UAV missions and D-GNSS surveys. Due to the pre-mature closure of field campaign, in total, six GCPs were only collected, among them only one GCP is within the ER1, i.e. glaciated region of the surveyed area. Remaining five GCPs were at the ER2 region where UAV trial survey was conducted on 2 October 2017 prior to the UAV flight on the glacier surface. Due to the poor GNSS satellite signal availability, the vertical (horizontal) RMSE of the DEM for ER2 was observed to be 31.83 m (1.74 m). However, for the same site after using GCPs, the vertical (horizontal) RMSE was reduced to 1.49 m (0.04 m).

**Hamtah** Here, the glacier’s valley surrounded by steep walls are comparatively steeper than East Rathong glacier valley. Such terrain conditions restricted the UAV’s GNSS module to receive fewer satellite signals (3–4 satellites) similar to that of East Rathong. Here, UAV take-off location was chosen outside the glacier region, as there was no appropriate place found for UAV take-off and landing around the glacier terminus region. During the flight, the link between UAV and GCS was lost for about twenty to thirty seconds because of steep wall glacier valleys and hence, UAV’s mission was called off. After several attempts, UAV took off again but still received only three to four GNSS satellites throughout the survey. Unexpectedly, the sudden change in weather followed by heavy snowfall in subsequent days led us to abort the planned missions. During the D-GNSS survey, 15 GCPs were collected (see Fig. 4b), but only five GCPs are lying inside the UAV surveyed glacier site because the mission was aborted as mentioned earlier. Unlike natural targets used in the East Rathong glacier, here artificial targets (see Fig. 4b) were used for collecting GCPs. The steep-walled glacier valleys obstructed the UAV survey and led to cover a smaller surface area than what was planned. Such obstruction was also one of the reasons to affect the accuracy of the UAV data products (see Table 5).

**Panchinala-A** Here, the glacier valley’s topography is relatively better than East Rathong and Hamtah glaciers. Therefore, the UAV GNSS module was able to acquire 9–12 satellite signals. Most of the glacier surface was covered by snow, and remaining snow-free area was covered by debris and boulders. For UAV landing, the only option that was available to us is on the snow-covered surface. However, the ground sensor module of the UAV identified snow as an obstruction. It is because the ground sensor used in the eBee X UAV identifies and alerts smooth textured surfaces like water, snow, or sand as obstruction in proximity. Hence, it took additional time (~ 15 min) to hover around and then finally crash landed on a nearby heavy debris surface, which was away from the planned landing location. As a result, the UAV faced major damages (severe damage in servo connection mechanism which connects aileron of wings with the central body of UAV). Therefore, to avoid such challenge, it is suggested to disrupt the ground’s uniform white surface, i.e. snow cover with artificial landing markers on flat surface areas at the landing location or else, the ground sensor (if available) should be turned off.

Based on these observations at three glacier sites, it is found that the challenges faced during UAV data acquisition varies majorly due to (i) nature of a glacier terrain and

| Glaciers          | Problems faced                                      | Causes                                      | Implications                                                                 |
|-------------------|-----------------------------------------------------|---------------------------------------------|-------------------------------------------------------------------------------|
| East Rathong      | Low GNSS signal reception                           | Steep valley walls at lateral sides of the glacier | Low DEM accuracy (without GCP targets); UAV landed 20–30 m away from the target location; minor damages on UAV |
| (ER1 and ER2 sites) | (3–4 GNSS station signals)                          |                                             |                                                                                |
| Hamtah            | Low GNSS signal reception                           | Steep valley walls at lateral sides of the glacier | Low DEM accuracy (without GCP targets); UAV landed 40-50 m away from the target location |
|                   | (3–4 GNSS station signals)                          |                                             |                                                                                |
|                   | UAV–Ground station link off (~ 30 s)                 |                                             |                                                                                |
| Panchimala-A      | UAV crash-landed on boulders rather than landing at assigned location on the snow-covered area | Snow cover (at landing location) was identified as obstruction by UAV’s ground sensor | UAV landing delayed and significant damages to servo connection mechanism (connects aileron with the central body of UAV) |
its margins and (ii) choice of UAV take-off/landing locations. Table 7 summarizes the challenges faced by fixed-wing UAV (eBee series) during data acquisition on three study glacier sites. Requirement of more GCPs can be avoided/reduced either using RTK enabled UAVs or PPK mode UAV surveys with high-quality on-board GNSS (Gaffey and Bhardwaj 2020). However, for any mode of survey, UAVs with onboard GNSS will require good satellite signal strength, which is weaker especially on the glaciers surrounded by steep lateral margins. In such case, UAV should be flown at a certain height from locations where it can have good receptibility of GNSS signals and hence, it is essential to choose appropriate UAV take-off and landing locations.

**Recommended UAV Take-off/Landing Locations**

From the experiences gained during the UAV surveys at the three glacier sites, the study realizes the importance of the site selection for UAV take-off and landing. When such sites are located, during fixed-wing UAV surveys (standalone GNSS mode) one can expect good satellite signal reception and avoid damages of the UAV hardware parts. In general, the UAV manufacturer (Sensefly, Original Equipment Manufacturer of eBee plus) recommends to perform take-off and landing the UAVs on a flat surface/mildly sloped terrains with 30 m offset around take-off/landing location and keep the ground sensor off (if present) to avoid damages. However, based on the knowledge gained from the challenges faced during the UAV surveys at three different glacier sites, the study recommends to choose a relatively flatter surface, preferably surface slope below six degrees. Similarly, instead of 30 m at least 50 m offset should be maintained around the identified UAV take-off/landing location to ensure minimum damages to UAV.

At the same time, it is observed that a single flight above 4000 m.a.s.l. may take ~ 20–40 min to cover 1.00–1.50 km² area with an average flying altitude ~ 175 m above the ground level (provided clear sky conditions, wind speed between 2 and 10 m/s, good GNSS satellite signal strength with low Dilution of Precision (DOP)). Accordingly, the study assumes that in glaciers located at such high altitudes having low temperatures, thin air density and relatively high wind speeds, 3–5 km² of glacier area can be covered in multiple flights (preferably in the mornings) using fixed-wing UAVs (such as eBee series) within a limited time window available in any given single day during ablation season.

Based on these observations and field experiences, the study has identified three potential sites favourable for UAV take-off and landing on Himalayan valley-type glaciers. A sample list of the potential glaciers (named ones) in Indian Himalayas where UAV surveying of whole glacier is possible using fixed-wing UAVs (such as eBee Plus/X) is given in Appendix along with the preferred sites for UAV take-off and landing.

**Top of the Glacier Valley**

In valley glaciers, the study recommends for UAV survey from the valley top adjacent to the glacier rather than the glacier surface region. Surveying from the glacier surface, UAV may use around 15–30% power of the battery (here, 3700 mAh batteries were used) to reach the desired altitude and landing after the end of the survey. When the UAV survey is conducted from the flatter/low relief regions (if available) of the valley top adjacent to the glacier, battery power used by the UAV and its flight time to reach the maximum altitude and landing can be significantly reduced. As a result, UAV can cover additional glacier area by saving UAV flight time to reach assigned height and landing at same flight conditions. Moreover, UAV tends to have a better field of view and can acquire maximum satellite signals with low DOP. In such cases, the number of flight attempts gets reduced, and the risk of damages can be minimized. However, to identify such locations, the guidance of field experts is essential.

**Near the Equilibrium Line Altitude (ELA)/Upper Ablation Region**

When no such recommended sites are identified on the valley top adjacent to a glacier, the locations near the ELA should be considered. Usually, the area near the ELA in Himalayan glaciers has wide cross-sections and exposed with hard ice without any debris cover. Hence, the landing of a UAV (fixed wing) on hard ice surface will avoid causing major damages to the UAV than the damages that occur while landing on the debris area. Moreover, the chances for maximum GNSS satellite signal receptions and the probability of covering a larger area are also better, i.e. UAV flights can cover both the accumulation and ablation regions from the same take-off and landing location.
Near the Terminus and Ablation Region

When the above two regions are not possible to occupy, then either the adjacent areas of ablation zone or glacier terminus and nearby downstream areas should be considered. For example, the studies by Kraaijenbrink et al. (2016a, b) and Kraaijenbrink et al. (2018) have chosen the take-off/landing site on eastern moraines in Lirung glacier and on western moraines in Lantang glacier, respectively, which lies in the ablation region. Generally, the terminus of the valley glaciers has narrow cross-sectional width and more terrain undulations than the areas near to ELA/upper ablation regions, which limits the coverage area of UAV survey to the ablation region and has a lesser chances of covering an entire glacier in a single flight if the glacier area is > 1 km². However, fixed-wing UAVs such as eBee series would be able to cover a whole glacier in a single flight under ideal flying conditions when launched from areas near terminus, if the glacier’s, i) area is less than 1 km², ii) elevation range is within 1 km, which helps to restrict the elevation gain by UAV to less than or equal to 1 km and iii) terrain has low relief valley similar to Panchinala-A glacier.

Conclusions

This article reports the first-hand experiences obtained from UAV surveys conducted using fixed-wing UAV (eBee series) on the glaciers located in Western and Eastern Indian Himalayas. Automated UAV surveys were able to cover the rugged and harsh terrains of the ablation zone across East Rathong glacier (in October 2017), Hamtah glacier (in September 2018) and Panchinala-A glacier (in June 2019).

From the UAV collected photographs, ultra-high spatial resolution (0.1 m GSD) DEMs and ortho-mosaicked images were generated by standard photogrammetric techniques. The study assessed the accuracy of UAV-derived DEMs with and without GCPs. Obtained results reveal that the UAV-derived DEMs without GCPs are highly prone to errors at steep-walled valley glaciers like East Rathong and Hamtah, and the DEMs derived with GCPs in these two glacier regions showed significant improvement in their accuracies. Whereas, at relatively low relief terrains like Panchinala-A glacier, DEM generated without GCPs are less prone to errors and only minor improvement is observed when the DEM was generated with GCPs. These observations show that glaciers with steep valley walls at their margin will need a greater number of GCPs to achieve decimetre level accuracy.

From the UAV surveying experiences on three glacier sites, the study recognised that choosing appropriate locations for UAV take-off and landing is one of the crucial aspects of a successful UAV survey. Furthermore, the study recommends strategies for choosing appropriate take-off/landing locations for UAVs, especially for fixed-wing UAVs. By following these recommendations, one can optimize the flight endurance, and increase coverage area on high mountain glaciers. The knowledge developed from this study can be valuable information to the glaciologists and hydrologists interested in using UAVs for mapping and monitoring of glaciers in the Himalayan region and possibly beyond. Despite fixed wing UAVs provide higher coverage and higher endurance, the major limitation is its inability to take-off or land vertically. Therefore, care should be taken to avoid take-off and landing of fixed-wing UAVs on the glacier surface where steep slopes and heavy debris exist. Another option is to use hybrid UAVs (fixed wing with vertical take-off/landing capability), which gives the advantages of both fixed wing and rotor wing UAVs on harsh glaciated terrains.

Appendix

See Table 8.
Table 8  Sample list of the potential glaciers in Indian Himalayas suitable for UAV surveying of whole glacier using fixed-wing UAVs (here eBee series)

| S. no | Glacier name (River basin) | Location | RGI 6.0 ID | Area (km²) | Debris cover (km²) | Elevation range (km) | Preferred sites for UAV take-off/landing (Expected number of flights to cover full glacier from the preferred take-off site) | Remarks |
|-------|-----------------------------|----------|------------|------------|-------------------|----------------------|------------------------------------------------|-----------------|
| 1     | Baralacha La (Chandra Basin) | 32°42'N 77°24'E | RGI60-14.14321 | 1.39       | 0.15              | ~ 0.50               | ✓ (1) ✓(1)                                                  | Both ELA and glacier terminus area are suitable sites for take-off and landing, from which whole glacier can be surveyed due to its small size. |
| 2     | Patsio (Bhaga Basin)        | 32°45'N 77°19'E | RGI60-14.14311 | 2.60       | 0.38              | ~ 0.92               | ✓ (2) -                                                     | Terrain near ELA is relatively flat with no debris and hence, it is preferred as suitable site for take-off and landing. |
| 3     | Garang (Baspa Basin)        | 31°28'N 78°25'E | RGI60-14.12386 | 4.32       | 0.68              | ~ 1.07               | ✓ (3) -                                                     |                                                                |
| 4     | Shaune Garang (Baspa basin) | 31°17'N 78°20'E | RGI60-14.12323 | 3.39       | 1.02              | ~ 1.2                | ✓ (2) ✓(1)                                                  | Due to large area, 60% of the glacier can be covered from locations near ELA and remaining 40% area (mainly near terminus) from sites near glacier terminus. |
| 5     | Neh Nar, (Jhelum Basin)     | 34°09'N 75°31'E | RGI60-14.19544 | 1.47       | 0.6               | ~ 1.11               | ✓ (3) -                                                     | Terrain near ELA is relatively flat with no debris and hence, it is preferred as suitable site for take-off and landing. |
| 6     | Batal (Chandra Basin)       | 32°20'N 77°34'E | RGI60-14.16042 | 4.05       | 1.27              | ~ 1.67               | ✓ (3) ✓(1)                                                  | Due to long glacier trunk, accumulation and upper ablation areas are expected to be covered from locations near ELA and remaining area (lower ablation) site near glacier terminus. |

This sample list of potential glaciers in Indian Himalayas is chosen after considering the following criteria such as, a) glacier should be 25 km away from International boundary (DGCA, 2018; accessed on 06 November 2020)\(^1\); b) maximum UAV flight height restriction of ~ 5900 m.a.s.l as per original equipment manufacturer recommendations.

\(^{\text{a}}\)The expected number of flights is calculated assuming that, on a given day, a single flight of fixed-wing UAV (here eBee series) covers ~ 1.00–1.50 km² area in ~ 20–40 min at an average flight height of ~ 175 m above ground level under clear sky and good weather conditions provided the maximum elevation gain of the UAV is below 1 km.

\(^{\text{b}}\)Details of the glacier area, debris cover area and elevation range are obtained from Randolph Glacier Inventory (RGI) 6.0.

By having a repeated time lapsed full coverage of glaciers, one shall able to perform annual mass balance calculations using geodetic method. It shall be noted that these glaciers are recommended solely based on the limited field experiences of the authors in operating UAVs in three different glaciers within Indian Himalayas. Therefore, it is strongly recommended to have field reconnaissance and detailed pre-flight analysis before flying to ensure successful UAV-based surveying.

\(^{\text{c}}\)Office of the Director General of Civil Aviation (DGCA), Government of India, Public notice on “Requirements for Operation of Civil Remotely Piloted Aircraft System (RPAS)”, New Delhi, 2018, 11

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Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

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