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Review

UAVs as remote sensing platform in glaciology: Present applications and future prospects

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ABSTRACT

Satellite remote sensing is an effective way to monitor vast extents of global glaciers and snowfields. However, satellite remote sensing is limited by spatial and temporal resolutions and the high costs involved in data acquisition. Unmanned aerial vehicle (UAV)-based glaciological studies are gaining pace in recent years due to their advantages over conventional remote sensing platforms. UAVs are easy to deploy, with the option of alternating the sensors working in visible, infrared, and microwave wavelengths. The high spatial resolution remote sensing data obtained from these UAV-borne sensors are a significant improvement over the data obtained by traditional remote sensing. The cost involved in data acquisition is minimal and researchers can acquire imagery according to their schedule and convenience. We discuss significant glaciological studies involving UAV as remote sensing platforms. This is the first review work, exclusively dedicated to highlight UAV as a remote sensing platform in glaciology. We examine polar and alpine applications of UAV and their future prospects in separate sections and present an extensive reference list for the readers, so that they can delve into their topic of interest. Because the technology is still widely unexplored for snow and glaciers, we put a special emphasis on discussing the future prospects of utilising UAVs for glaciological research.

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1. Introduction

Glaciers are now a confirmed and well-observed proxy for estimating the extent of changing global climate (Oerlemans, 2005). Large-scale shifts in the areal, altitudinal, and flow regimes of glaciers are bound to promote glacial disasters (Debella-Gilo & Kaab, 2011) and hydrological irregularities (Immerzeel, van Beek, & Bierkens, 2010), necessitating their worldwide monitoring (Haeberli, Cihlar, & Barry, 2000; Kargel et al., 2005). Year-round, field-based glacier monitoring is limited by several factors such as hostile climate, poor approachability, and inadequate labour and funding (Bhardwaj, Joshi and Sam, 2015a). In such scenarios,

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remote sensing is largely utilised as a practical alternative to field studies in order to meet the growing needs of glaciological research.

Space-borne remote sensors have high temporal and global coverage and remote sensing-based analysis reduces the need for frequent or prolonged visits to glacial terrain. However, space-borne remote sensing platforms have their own limitations. One cannot expect data to be acquired on specific dates or at a specific time. Data acquisition depends upon the satellite's revisit or temporal resolution. If the satellite sensors do not operate in microwave wavelengths, obtaining cloud-free data is yet another challenge. The improved spatial resolutions of satellite sensors has resulted in smaller pixel sizes, but the cost of this sub-meter resolution data (e.g., GeoEye and WorldView) is too high for large-scale glacier monitoring. These limitations can easily be overcome by the use of unmanned aerial vehicles (UAVs). UAVs are remotely controlled, uninhabited, reusable motorized aerial vehicles that can carry various types of payloads or cameras designed for specific purposes. Such platforms provide the flexibility to choose appropriate data acquisition periods and data types (multispectral, hyperspectral, thermal, microwave, LiDAR). It also facilitates the adjustments in flying heights, to obtain very high spatial resolution while maintaining viewing angles and forward and side overlap dimensions. The cost of these data acquisition methods is substantially lower than that of high-resolution satellite imagery. UAV-based remote sensing has the potential to bridge the gap between sparse and discontinuous field observations and continuous but coarse resolution space-borne remote sensing. Although the use of UAVs in glaciological research is still in its infancy, the future prospects of this technology are immense. This new approach of using UAV platforms, as well as the advances in photogrammetry is proving to be very effective in glaciological research (Hugenholtz et al., 2013). By using UAVs, it is now possible to capture imagery at sub-centimetre resolution and with high positional accuracy. The advent of lightweight, low-cost UAVs coupled with various remote sensors is revolutionising research prospects in glaciology. In addition to hardware developments, software packages such as Bundler (e.g., Fonstad, Dietrich, Courville, Jensen, & Carbonneau, 2013), Microsoft PhotoSynth, and Photoscan (e.g., Turner, Lucieer, & Watson, 2012), are effectively contributing to the production of accurate and high resolution Structure from-Motion (SfM)-based digital surface models (DSMs), digital terrain models (DTMs) and ortho-mosaics of mountainous terrain. The UAV acquired images can be directly input to these software packages. A DTM is a generic term, normally implied for the elevation of bare earth, without vegetation and buildings (Maune, Kopp, Crawford, & Zervas, 2001), or for variables such as digital elevation models (DEMs), gradient, aspect, and curvature, relating to a topographic surface (Florinsky, 1998). A DSM, on the other hand, depicts elevations of the top of reflective surfaces, such as buildings and vegetation (Maune et al., 2001). Both of these elevations products can be accurately generated using UAV-acquired images and SfM tools. Using UAV as an aerial platform has another significant advantage, which is avoiding the possibility of fatal crashes of manned aircrafts, particularly in inclement weather conditions in high mountains.

Several key research papers and review articles have already discussed the hardware components, features of various commercial UAVs, and their cross-disciplinary applications (e.g. Colomina & Molina, 2014; Hardin & Jensen, 2011; Nex & Remondino, 2013; Watts, Ambrosia, & Hinkley, 2012; Whitehead & Hugenholtz, 2014; Whitehead et al., 2014). However, we could clearly observe three research gaps: (1) a lack of any review, exclusively devoted to UAV applications in glaciology, (2) a lack of coverage of all the published papers on this topic, and (3) a lack of detailed suggestions on the future prospects of UAVs in glaciology. This helped us in framing the following objectives of the present review paper:

- To present a systematic survey of studies using UAVs for glaciological studies;
- to include all the published papers in the review, in order to serve as a better reference to the reader; and
- to suggest the future scopes and utilisation potential of UAVs in glaciological research.

This paper not only reviews the past and present status of UAV technology in glaciology but also suggests the future potential of UAVs to promote multidisciplinary research on glaciers. We start by presenting a brief history of the evolution of UAVs. In the following sections, we discuss several pioneering studies using UAVs for glaciological research. We discuss the achievements of these studies and opportunities for improvement, where they exist. Next, we present a detailed conclusion highlighting the importance of UAV platforms and their possible future contribution to glacier studies. This section highlights the major points of the review, which not only recognizes the value of the efforts of pioneer researchers but also guides those interested in UAVs to partake in this exciting prospective research. A relevant compilation of references helps the reader to further explore this topic. The data shown in this paper and the discussion focus on only studies that have been published as complete research articles in peer-reviewed journals and magazines or as peer-reviewed university degree theses. We have not included book chapters or unpublished conference proceedings. To the best of our knowledge, we have tried to identify and discuss the significant studies within this research domain, and this paper is the first review of applications of UAV technology in glaciology.

2. Brief history

Before beginning the review of the present research and discussing future prospects, it is crucial to understand the history of UAV technology. The following sub-sections concisely discuss the advent of UAVs and their introduction to civilian research.

2.1. Synonyms and definitions

UAVs are popularly called by several synonymous terms such as unmanned aircraft systems (UASs), drones, remotely piloted aircrafts and aerial robots. The term "UAS", however, refers to an entire system consisting of a UAV as the platform, the payloads and the ground segment controlling the UAV. While the United States Department of Defence (DOD) and the Civil Aviation Authority (CAA) of the United Kingdom prefer the term "UAS" (Colomina & Molina, 2014), the International Civil Aviation Organization (ICAO) uses Remotely Piloted Aircraft System (RPAS) to refer to a UAV (ICAO, 2011). ICAO (2011) defines RPAS as "a set of configurable elements consisting of a remotely piloted aircraft, its associated remote pilot station(s), the required command and control links and any other system elements as may be required, at any point during flight operation". This definition may sound complicated, but it is one of the most holistic definitions of a UAS, as it includes both aerial and ground segments of UAS. An earlier definition by Peter van Blyenburgh (1999) described UAVs as remotely controlled, uninhabited, reusable, motorized aerial vehicles capable of carrying various types of payloads for remote sensing missions. Eisenbeiss (2008) originally introduced the term "UAV photogrammetry" as a platform for photogrammetric acquisitions, which can be semi-autonomously or autonomously remotely controlled. If we combine these definitions, as per our understanding, a UAS in remote sensing and photogrammetric terms may be concisely defined as follows:

> A system comprised of a ground segment that remotely controls an aerial segment consisting of an unmanned aerial vehicle carrying various remote sensors for capturing high resolution data of the terrain, further enabling the possibility of photogrammetric applications of the gathered data

In the present review, we exclusively focus on the UAVs as remote sensing platform and do not discuss the payloads and ground segment of a UAS. Therefore, in rest of the paper, the term "UAV" is preferred.