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Fully-automated estimation of snow depth in near real time with the use of unmanned aerial vehicles without utilizing ground control points

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ABSTRACT

A new method for on-demand production of a numerical snow depth map, based on observations carried out in near real time by an unmanned aerial vehicle (UAV), is elaborated. The novelty of the approach resides in the neglection of artificial ground control points (GCPs). The method is based on processing oblique aerial geotagged images of snow-covered terrain taken with visible-light (RGB) camera installed on UAV. The compressed photographs (JPG format) are pre-processed with the use of parallel computing in order to resize the images. The structure-from-motion (SfM) procedure – herein based on the RunSFM solution – is utilized to generate a non-georeferenced dense point cloud. The subsequent automatic georeferencing procedure comprises two stages: (1) initial registration of the snow-covered dense point cloud using the Helmert transformation, the parameters of which are estimated from camera positions in local (image) and Universal Transverse Mercator (UTM) coordinate systems, (2) final registration of the snow-covered dense point cloud with the iterative closest point (ICP) algorithm applied in respect to a reference snow-free and highly accurate dense point cloud. The second phase is based on the automated ICP application to two subsets of these dense point clouds which include only tall land cover elements, mainly trees. This enables the ICP-based transformation of the source (with snow) dense point cloud into the reference one (snow-free). The two dense point clouds are subsequently interpolated to digital surface models (DSMs), the difference of which forms a numerical map of the estimated snow depth. The procedure is tested on the RGB images taken by the micro fixed-wing UAV in the Izerskie Mountains in southwestern Poland. In addition, a reproducibility test, which compares the above-mentioned procedure with its replica based on modified settings (NIR camera, lower flight altitude, bigger number of images, higher resolution, SfM reconstruction produced with Theia and OpenMVS), is also performed. The estimation is validated against spatially-distributed snow depth measurements. It is found that the method resolves snow depth with a correct order of magnitude. Mean absolute error (MAE) of snow depth estimation varied between 0.33 and 0.43 m, whereas measured snow depths were between 0.24 and 1.06 m (mean of 0.41 m). Medium level of reproducibility is reported, with considerable similarity in statistics of snow depth estimation and only partial (local) agreement between spatial patterns of estimated and measured snow depth fields. In addition, the results show potential for using NIR images in producing realistic estimated snow depth surfaces.

1. Introduction

Snow depth (HS) and snow bulk density (ρb) control water storage in snow cover, and the latter retention effect is quantitatively expressed by snow water equivalent (SWE) (Elder et al., 1998). The information on how much water is stored in a river basin is crucial for water management purposes, particularly for forecasting snowmelt high flows. In order to provide such information in near real time, both HS and ρb should be routinely measured which is carried out within hydrometeorological observational networks. Such measurements are pointwise, and usually observational sites are sparsely and non-evenly distributed. For hydrological applications, however, spatial information on SWE within a basin is required to infer the snow-induced hydrograph dynamics at downstream gauges. In addition, for a purpose of flood risk management these estimates should be available in near real time.

In order to produce the spatial SWE estimates, not only information on ρb should be known, but also spatially continuous estimates of HS are needed. Snow density, however, can be calculated from meteorological data (Meløysund et al., 2007) or using the empirical model based on the power function and calibrated on a basis of snow depth-density data (Jonas et al., 2009).

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Classical measurements of HS are carried out *in situ*, at discrete points of geographical space, and such pointwise data become inputs to interpolation procedures, for instance based on kriging (Dyer and Mote, 2006; Pulliainen, 2006). Point measurements of HS can also be carried out using the ground-penetrating radar (Buchroithner et al., 2008). Terrestrial light detection and ranging (LiDAR) and tachymetric measurements can also serve a purpose of acquiring spatial data on HS (Grünewald et al., 2010; Prokop, 2008; Prokop et al., 2008; Schön et al., 2015). There are also numerous HS products which are based on observations from satellites and aircrafts. The example applications use: Moderate Resolution Imaging Spectroradiometer (MODIS) (Hall et al., 2002), Geostationary Operational Environmental Satellite (GEOS) (Romanov and Tarpley, 2007) or airborne LiDAR technology (Deems et al., 2013).

Recent advances in monitoring snow cover are due to aerial photogrammetry, both its traditional version with sensors mounted on manned aircrafts (Bühler et al., 2015; Cline, 1993) and its low-cost alternative which makes use of oblique images acquired by consumer-grade cameras installed on manned aircrafts (Nolan et al., 2015) or unmanned aerial vehicles (UAVs) (Bühler et al., 2016; de Michele et al., 2016; Harder et al., 2016; Vander Jagt et al., 2015). The main idea behind the reconstruction of HS from the UAV-taken images is based on subtracting a snow-free digital surface model (DSM) from a DSM with snow cover, following a standard concept known as DoD which is an abbreviation from DEM (digital elevation model) of difference. The two DSMs can be computed from dense point clouds generated using the structure-from-motion (SfM) algorithm. Laser scanning and photogrammetry have recently been combined for HS mapping purposes (Prokop et al., 2015).

Although the use of SfM for HS determination is well-documented, there are considerable problems with the accuracy of these estimates (Harder et al., 2016). The reasons of the errors may reside in many environmental and technical problems, one of which is georeferencing also known as registration. To build a well-georeferenced dense point cloud using SfM, and consequently a DSM of snow-covered terrain, it is necessary to work with artificial or natural ground control points (GCPs), also named as reference points (RPs). Their coordinates should be measured directly in the field using a precise GNSS (Global Navigation Satellite System) receiver. Vander Jagt et al. (2015) argue that "if snow depth can be accurately resolved without GCP information, areas could be directly mapped without the need to expose field personnel to dangerous weather conditions". Likewise, Bühler et al. (2016) claim that "the distribution of the artificial RPs is time-consuming and a meaningful distribution over the test site is often not possible due to e.g., avalanche danger". In order to improve safety and to reduce time needed to generate a HS map, there is a need to elaborate methods which allow to omit either placing GCPs physically on snow cover or measuring their coordinates. Such a method is proposed in this paper, and a key motivation for its elaboration is that it becomes a part of a larger system which aims to estimate HS and SWE in near real time for water management purposes. The experimental platform, including UAVs and a mobile laboratory, is presented in Fig. 1.

The novelty of our approach resides in its two features. Firstly, our method for georeferencing dense point clouds, obtained from the SfM-processed images taken by a UAV without GCPs, differs from a recent proposition offered by Vander Jagt et al. (2015). To omit GCPs these authors use the direct bundle adjustment which utilizes the airborne aerotriangulation known also as the direct georeferencing. Our method is different since it integrates (1) initial georeferencing of a snow-covered dense point cloud using the Helmert transformation based on camera positions in local (image) and Universal Transverse Mercator (UTM) coordinate systems with (2) final registration which employs the iterative closest point (ICP) algorithm to provide a fix of this dense point cloud to a reference, snow-free dense point cloud. Secondly, the entire procedure is designed to

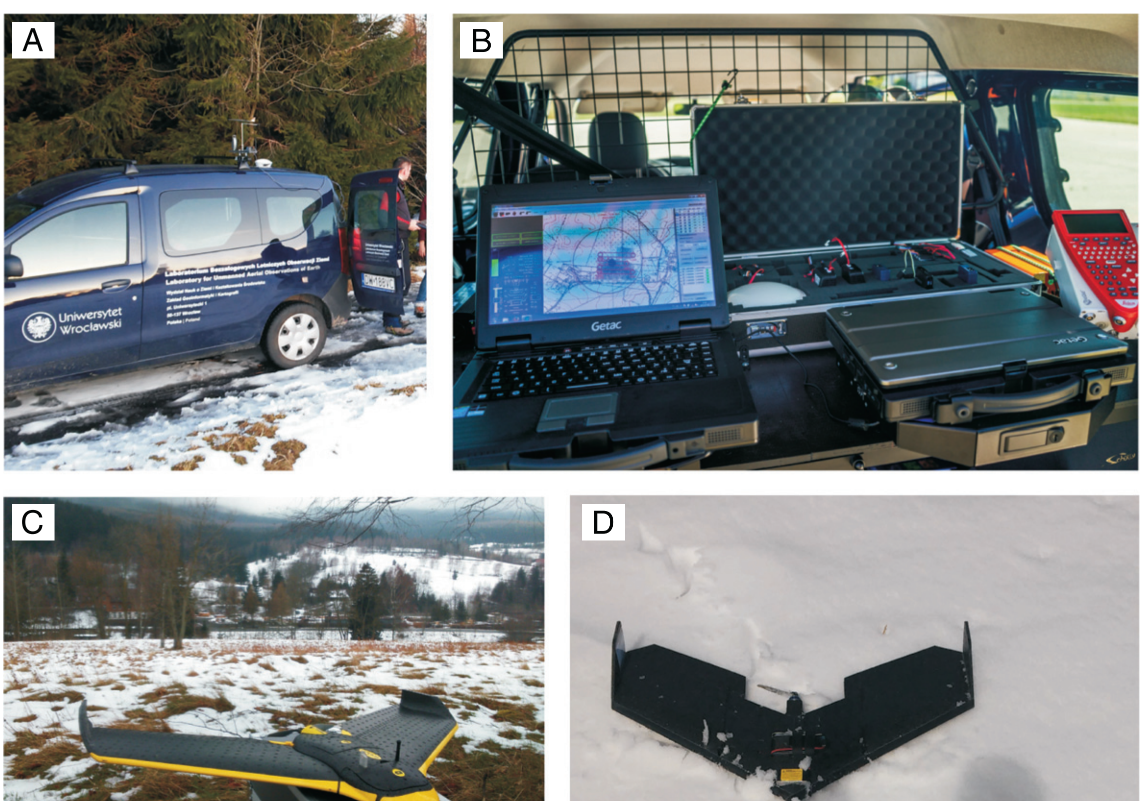

Fig. 1. Laboratory for Unmanned Aerial Observations of Earth of the University of Wrocław: vehicle with radio modem, GNSS antenna and meteorological equipment installed on roof (A); computational unit within vehicle (B); eBee drone (C); swinglet CAM drone (D).