歷史影像的運動回復結構：自動化處理的歷史航空影像進行長期地形變化分析

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摘要

準確地測量地球表面在十年到百年之間的變化對於許多科學和工程應用至關重要，然而長期的定量地形變化記錄在時間和空間上分布仍較為不足。歷史航空影像的掃描檔提供了一個可以透過精準高程測量來補充這些記錄的機會，以捕捉地表的歷史狀態。利用運動回復結構（Structure from Motion，SfM）可以從這些歷史圖像中生成高品質的數值高程模型(Digital Elevation Model，DEM）和正射影像，但是手動的影像預處理和選擇地面控制點等作業阻礙了大規模的處理。我們開發了一種自動化方法來處理歷史圖像並生成高解析度（0.5-2 米）DEM 和正射影像序列，且無需手動選擇地面控制點。方法藉由 SfM 來校正相機內部及外部參數，並使用現代地形資料做為參考，進行高精度的多階段配準來改進地理定位。我們使用北美冰川航空攝影資料庫中 1967 年至 1997 年間的掃描影像來演示這種方法，並展示了華盛頓州的兩處具有不同影像獲取幾何和重疊（貝克山和南卡斯卡德冰川）的成果。該自動化方法能夠校正數公里的初始相機位置誤差，並生成精準地理定位的高解析度 DEM 和正射影像，不受相機參數、獲取幾何、地形特徵和參考 DEM 解析度的限制。在貝克山，我們使用了 1970 年至 1992 年間共 261 張影像並生成 10 個 DEM，在光束平差調整優化後，平均 RMS 重投影誤差為 0.67 像素（0.15 米）；南卡斯卡德冰川則使用在 1967 年至 1997 年間共 243 張影像並生成 18 個 DEM，平均 RMS 重投影誤差為 0.65 像素（0.13 米）。在歷史時序分析中，貝克山的相對高程精度為 0.68 米，南卡斯卡德冰川為 0.37 米。與使用 SfM 和手動選擇地面控制點所生成的 DEM 相比，我們的成果降低了系統

誤差並提高了準確性。在 30 年的時間內，最終的高程變化測量精度為 0.7-1.0 米，並且可以觀察速率低至 1-3 公分/年的地表變化。我們的結果展示了具潛力的新量化方法，可以大量且迅速處理歷史影像資料，並提供長期大地測量變化和地表演化。

關鍵字： 攝影測量、套合、地形、地表、高程、DEM、時間序列、冰河、NAGAP

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Historical Structure from Motion (HSfM): Automated processing of historical aerial photographs for long-term topographic change analysis

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ABSTRACT

Precisely measuring the Earth's changing surface on decadal to centennial time scales is critical for many science and engineering applications, yet long-term records of quantitative landscape change are often temporally and geographically sparse. Archives of scanned historical aerial photographs provide an opportunity to augment these records with accurate elevation measurements that capture the historical state of the Earth surface. Structure from Motion (SfM) photogrammetry workflows produce high-quality digital elevation models (DEMs) and orthoimage mosaics from these historical images, but time-intensive tasks like manual image preprocessing (e.g., fiducial marker identification) and ground control point (GCP) selection impede processing at scale. We developed an automated method to process historical images and generate self-consistent time series of high-resolution (0.5–2 m) DEMs and orthomosaics, without manual GCP selection. The method relies on SfM to correct camera interior and exterior orientation and a robust multi-stage co-registration approach using modern reference terrain datasets for geolocation refinement. We demonstrate the method using scanned images from the North American Glacier Aerial Photography (NAGAP) archive collected between 1967 and 1997. We present results for two sites with variable photo acquisition geometry and overlap — Mount Baker and South Cascade Glacier in Washington State, USA. The automated method corrects initial camera position errors of several kilometers and produces accurately georeferenced, high-resolution DEMs and orthoimages, regardless of camera configuration, acquisition geometry, terrain characteristics, and reference DEM properties. The average RMS reprojection error following bundle adjustment optimization was 0.67 px (0.15 m) for the 261 images contributing to 10 final DEM mosaics between 1970 and 1992 at Mount Baker, and 0.65 px (0.13 m) for the 243 images contributing to 18 individual DEMs between 1967 and 1997 at South Cascade Glacier. The relative accuracy of elevation values in the historical time series stacks was 0.68 m at Mount Baker and 0.37 m at South Cascade Glacier. Our products have reduced systematic error and improved accuracy compared to DEM products generated using SfM with manual GCP selection. Final elevation change measurement precision was ~0.7–1.0 m over a 30-year period, enabling the study of processes with rates as low as ~1-3 cm/yr. Our results demonstrate the potential of this scalable method to rapidly process archives of historical imagery and deliver new quantitative insights on long-term geodetic change and Earth surface processes.