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REVIEW ARTICLE

Geoprocessing of archival aerial photos and their scientific applications: A review

Adam Kostrzewa [1*]

[1]Department of Photogrammetry, Remote Sensing and Spatial Information Systems, Faculty of Geodesy and Cartography, Warsaw University of Technology, Pl. Politechniki 1, 00-661, Warsaw, Poland

[*]adam.kostrzewa.dokt@pw.edu.pl

Abstract

Poland as well as other countries keep extensive collections of 20th and 21st-century aerial photos, which are underexploited compared to such other archival materials as satellite imagery. Meanwhile, they offer significant research potential in various areas, including urban development, land use changes, and long-term environmental monitoring. Archival photographs are detailed, often obtained every five to ten years, and feature high resolution, from 20 cm to 1 m. Their overlap can facilitate creating precise digital models that illustrate topography and land cover, which are essential variables in many scientific contexts. However, rapidly transforming these photographs into geographically accurate measurements of the Earth's surface poses challenges. This article explores the obstacles in automating the processing of historical photographs and presents the main scientific research directions associated with these images. Recent advancements in enhancing workflows, including the development of modern digital photogrammetry tools, algorithms, and machine learning techniques are also discussed. These developments are crucial for unlocking the full potential of aerial photographs, making them easier accessible and valuable for a broader range of scientific fields. These underutilized photographs are increasingly recognized as vital in various research domains due to technological advancements. Integrating new methods with these historical images offers unprecedented opportunities for scientific discovery and historical understanding, bridging the past with the future through innovative research techniques.

Key words: photogrammetry, remote sensing, historical photos, multi-temporal, geoprocessing of aerial imagery

1 Introduction

Progress in photogrammetry is primarily driven by advancements in sophisticated digital image processing software. The integration of Computer Vision (CV) technology, Structure-from-Motion (SfM) algorithms, and automatic feature detection in images has greatly expedited and simplified all stages of the Earth's surface model development using aerial photographs.

The introduction of new digital image processing techniques has sparked renewed interest in archival photos as a spatial data source. The growing popularity of these historical images is primarily attributed to their potential for reducing time-consuming data processing and enabling automated processing. Consequently, a vast repository of archival images, spanning back as far as a century ago, will be utilized more efficiently. These data are particularly valuable as they offer an irreplaceable and detailed perspective of historical landscapes.

Advancements in specific research areas are bringing the processing and utilization of archival images closer to that of modern digital images. The progression towards automated workflows is nearing completion, encompassing effective archiving and preservation of images, the establishment of guidelines for creating digital copies, and the production of photogrammetric products ready for geoprocessing and information extraction. Developing appropriate algorithms and processing guidelines is significantly facilitating the broader adoption of these novel remote sensing techniques.

The increased interest in this topic can be mainly seen in various types of scientific publications. This trend can be

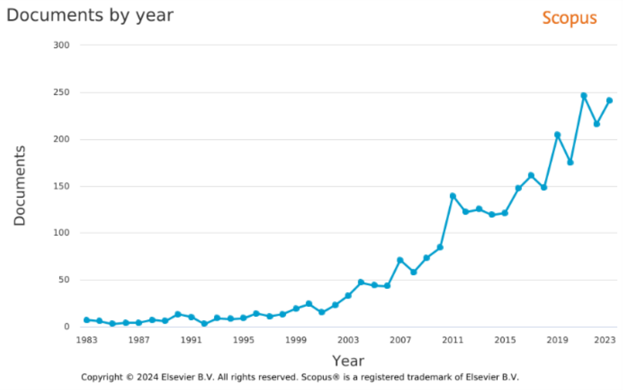

Figure 1. Number of results for query: TITLE-ABS-KEY (historical photos OR archival photos) in Scopus database

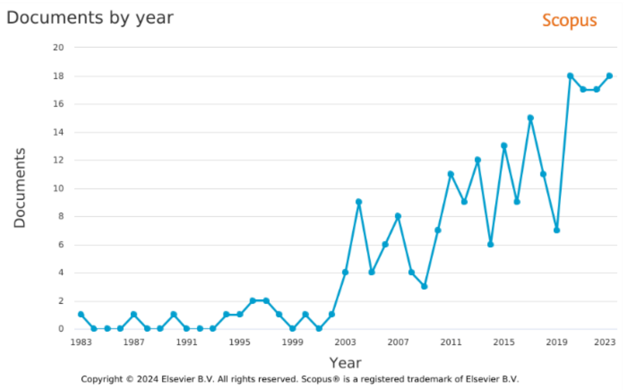

Figure 2. Number of results for query: TITLE-ABS-KEY(*processing AND (historical photos OR archival photos)) in Scopus database

seen in Figures 1 and 2, showing the number of publications from the last 40 years about archival and historical aerial photographs (Figure 1) and the processing of such data (Figure 2). A total of 2,825 articles were published between 1983–2023, with an almost twofold increase in publications in this area in in 2021 (249 publications) relative to a decade earlier – 2011 (145 publications). Processing (geoprocessing) was described in a maximum of 2 publications per year before 2003 as opposed to an average of 17–18 publications per year currently, which correlates with the latest technological advances and easier access to this kind of data. With the help of the VOSviewer tool, a visualization of the links between the keywords was made (Figure 3) which illustrates the main topics covered in the publications and their interrelationships.

To create this publication, three primary databases were used: Scopus, Google Scholar, and Web of Science. This review article presents the latest and most important findings and methodologies for using archival aerial photographs across diverse research domains. It emphasizes the primary outputs derived from these data, including orthomosaics and elevation models. The utility of aerial photos as a source for land cover and land use information is explored, highlighting their role in photointerpretation and comparison with contemporary data. Insights from this literature review provide a comprehensive perspective on archival photos, their myriad applications, and recent advancements in this field.

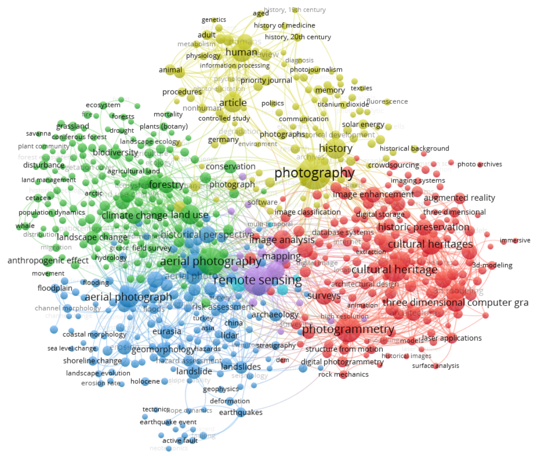

Figure 3. The visualization of the links between the keywords for query: TITLE-ABS-KEY (historical photos OR archival photos) in Scopus database

2 Assessment of Polish and European archival photos: present status and historical perspectives

In Poland, efforts to acquire aerial photos have been repeated regularly throughout the country since the mid-20th century. Over the past decade, these photos have been essentially scanned and are now available in digital form. Combining the resources of the Head Office of Geodesy and Cartography (*pl.* GUGiK) and the Central Archives of the Military Historical Office (*pl.* CAW WBH) yields more than 1.5 million analogue images of Poland's current territory.

In 1908, American pilot Wilbur Wright and photographer L. P. Bonvillain took the first aerial photos of Le Mans, France, thus opening the era of aerial photography. According to available source materials, it is assumed that the first aerial photo recording of the Polish territory was taken in 1915 as part of the intelligence activities of the armies fighting during World War I, and it depicted the area around Gorlice (Olędzki, 2009). The World War I conflict significantly popularized the technique of image acquisition. Aerial photographs were used to identify enemy positions and changed how warfare was conducted. In the interwar period, the task of acquiring photographs was mainly handled by the Military Geographical Institute (*pl.* WIG), established in 1918, and the Photogrammetric Department within it (Lisenbarth, 1991). Private companies, such as the "Fotolot", also began to perform photogrammetric work commercially. By the time of World War II, in Poland aerial photography had covered a total area of about 150,000 square kilometers , which was about 40% of the territory of the Second Polish Republic (Lisenbarth, 2000). After the war, Poland again focused on using aerial photographs to as guidance in the efforts to rebuild the country. Aerial photos were used for damage assessment, reconstruction planning, and military purposes (Wójcik, 1991).

In the 1950s and 1960s, Poland gradually introduced air flights into service for land mapping purposes. After the political transformation in the 1990s, the images were financed from various sources, and Poland actively participated in international projects, such as the PHARE (Poland and Hungary: Assistance for Restructuring their Economies) project (Kurczyński, 1997). In the years 2007–2011, analogue cameras were gradually replaced by a new generation of digital cameras, which initiated the era of digital aerial photography. In connection with the project of the Informatic System of National Defense against Extraordinary Hazards (*pl.* ISOK) implemented in 2011–

2015, aerial photos of 203 cities with a population exceeding 50,000 residents were taken and a digital orthophoto map with a resolution of 10 cm was developed (Kurczyński, 2014).

Currently, the GUGiK regularly develops the coverage of the country by adding aerial photos, updating selected areas in terms of timeliness and more favourable field resolution of the study. Local authorities order aerial imagery and orthophoto production to be able to address the regional needs more fully and flexibly. GUGiK continues to work on updating the country's coverage of aerial photos, planning a two-year cycle of acquiring images with a pixel resolution of 25 cm and more detailed data for larger cities.

Based on an analysis of data from various scientific publications, the size and characteristics of the different national aerial photo archives in Europe are as follows:

- Spain has about 582,000 analogue photos, most of which have already been digitized. The images are from different periods, and the archive is available to the public free of charge (Fernandez, 2022).
- Switzerland - the resource contains about 500,000 images: a unique collection, including aerial photographs and an orthophoto map amalgamated from them in 1946, covering 99.79% of the country (Jabrane and Heisig, 2022).
- France is estimated to maintain an archive of 3 million images of European areas and 1 million images of former French overseas possessions. Since 2003, France has acquired only digital photos to cover the entire country every 3–4 years (Truquin, 2019).
- Norway is estimated to have an analogue photo stock of 1.3 million negatives, half of which are to be digitized by 2029 (Buller, 2019, 2022).
- Czech Republic and Slovakia - the total resources are estimated at 700,000. The collection covers the period from the 1930s to the present, mainly related to military purposes (Dušánek et al., 2019).
- Sweden – has about 1.2 million negatives in cut film. In addition, the country has collected accurate raid metadata in the form of raid series maps. The digitization process is underway, and the collection dates to 1929. The country's surveying and mapping service also provides orthorectified images (Bygren and Hedqvist, 2019; Norin and Klitkou, 2022).
- Italy – the archive contains numerous collections dating to 1880. The collections include public and private photographs, which are expected to take about 25 years to digitize (Shepherd et al., 2019).
- Belgium – The archive has about 370,000 analogue photos from the Democratic Republic of Congo, Rwanda, and Burundi from 1947 to 1980, and the images are used for land cover change and natural hazard analyses (Kervyn, 2022).
- Denmark – The Danish archive consists of about 2,300 cans of uncut film and contains about 400,000 negatives of aerial photographs. The collection covers Danish and Greenlandic territory, with the oldest photos dating to years before 1950 (Nielsen and Dindorp, 2022).

3 Geoprocessing of historical aerial images

The growing interest in historical photographs has intensified efforts to consolidate research in this domain. Insights from the 1st European Spatial Data Research (EuroSDR)'s survey of 2017, as summarized by Giordano and Mallet (2019b), offer a comprehensive overview categorizing primary research areas and challenges encountered while working with archival datasets. Foremost among the challenges recognized by various research groups and national cartographic organizations is the production of orthoimagery from analogue aerial photographs. The survey highlights three principal difficulties: the lack of metadata, especially. camera calibration reports; the scarcity of ground control points (CPs), particularly challenging to locate in old analogue images; and the pressing need for automated methods to generate orthoimages, which could serve as crucial or intermediate products which could be widely used for a variety of purposes.

A notable presentation at the 2nd EuroSDR workshop in 2022 offered a comprehensive review and evaluation of the current practice of processing archival aerial photography (Piermattei, 2022). The study analysed described 149 scholarly papers that processed 363 sets of aerial photographs and 59 archival satellite scenes. They noted that most studies focusing on archival aerial photographs use relatively small datasets, with over half of them of fewer than 40 images. Furthermore, their analysis identified prevalent research directions and trends in processing methodologies and photogrammetric software. Specifically, over 60% of the projects adopted processing techniques rooted in SfM processes, Multi-View Stereo (MVS) techniques, and utilized the Agisoft Metashape program.

Giordano and Mallet (2019b) focused on the state of current practices regarding archival aerial photography and did not propose solutions or results of their new research. This form was prepared to obtain up-to-date information regarding supply and demand in the context of digitizing and sharing analogue aerial photographs in Europe. Piermattei (2022) categorized and proposed a general overview of recent research and methods in terms of mainly statistics, rather than major initiatives, new developments or their description. This publication delineates critical research about archival aerial photographs, elucidating notable progress in scanning analogue resources, automatic land cover classification and segmentation, grayscale image colorization, and analytical methodologies for image orientation. In addition, it is a certain extension of the mentioned items to include the most up-to-date studies that earlier authors did not cover. Synthesizing these studies, finding common parts, and analyzing the research conducted can help find research gaps in this area and help suggest future work.

3.1 Creating digital copies of analogue photos

Analogue aerial photographs degrade over time due to their physical medium, resulting in diminished quality. Historically, inadequate storage practices have exacerbated this issue, reducing the accuracy of photogrammetric processing (Falkowski et al., 2007). Recent decades have seen the development of effective storage methods to safeguard these images from environmental factors (Buller, 2019; Fernandez, 2022; Giordano and Mallet, 2019a). A permanent preservation solution emerged in the form of specialized photogrammetric scanners for digitizing analogue photos (Luman et al., 1997). Specific scanner parameters significantly impact digital copy quality, with geometric accuracy being paramount. Residual errors in scanner geometric accuracy should ideally be within 1–2 µm for optimal results (Mitrovic et al., 2004). The scanner's resolution capability, the second essential parameter, is measured in dots per inch (dpi), and it directly translates to the size of the scanning pixel (pixel of the new file). Radiometric resolution is another crucial parameter of scanning devices. To achieve optimal results when scanning a black-and-white film, it is recommended that a recording range of eight bits is used, due to the granularity of the emulsion, which introduces noise effects into the material (Baltsavias, 1999).

Seccaroni et al. (2018) investigated the impact of image digitization settings, including geometric and radiometric resolution, vis a vis the accuracy of output digital surface models (DSMs). They found that the optimum geometric resolution for scanning ranged between 800 and 1600 dpi, while radiometric resolution did not affect computation time or improve the quality of final DSMs. Comprehensive reviews of specialized photogrammetric scanners were conducted around the turn of the 20th and 21st centuries (Baltsavias, 1999; Baltsavias and Käser, 1999). While photogrammetric scanners are typically preferred for accurately archiving analogue aerial photographs, some researchers have found high-quality consumer-grade scanners to be effective alternatives, particularly for historical photographs with inferior geometry, such as those predating World War II. Several studies have examined the effects of non-professional, consumer-grade scanners on subsequent photogrammetric work. Sevara (2016) warns against using non-professional scanners, citing significant drawbacks such as non-uniform geometric distortions. Mitrovic et al. (2004) demonstrated that standard photogrammetric tasks could be effectively performed with regular scanners through additional calibration processes. They utilized a consumer-grade scanner, developing a process including scanning, calibrating the scanner, and correcting systematic distortions to maintaingood geometric accuracy. The cost of their approach was estimated to be approximately ten times lower than that of a professional photogrammetric scanner. Kostrzewa et al. (2024) present results that show the effect of using consumer-grade scanners on aerial triangulation and dense image matching.

The adoption of digital cameras for digitizing analogue photographs has gained popularity in recent times (Aleithe, 2022; Thomas, 2022). Various studies have discussed the efficiency of scanners like the AFS150, equipped with a Phase One IXM-MV150F camera, in comparison to traditional photogrammetric scanners like the Z/I Photoscan (Aleithe, 2022; Meixner, 2022; Schulz et al., 2021; Schulz and Herbst, 2022). Images produced by the AFS150 scanner are noteworthy for their post-correction geometric accuracy, reaching as low as 2 μm (Aleithe, 2022). Additionally, the speed of this device is notable, with reports of approximately 1000 scans completed in an 8-hour workday (Aleithe, 2022), whereas the photogrammetric scanner process took about 15 minutes per photo, equating to 24 photos in an 8-hour workday (Schulz et al., 2021). In a comparison study conducted by Schulz and Herbst (2022), scans made using non-professional devices underwent additional camera calibration using a model with 44 parameters during the aerial triangulation (AT) process. This supplementary step ensured that the accuracy of AT making analogue photo scans with the non-professional device was on a par with that achieved using a professional photogrammetric scanner. These studies suggest that while there is potential for Phase One cameras in digitizing analogue photos, bringing their quality and accuracy closer to that of professional devices, the economic justification for further experimentation over subsequent years may be limited. Given that most National Mapping and Cadastral Agencies (NMCAs) are expected to complete the creation of permanent digital archives within this timeframe (Bygren and Hedqvist, 2019), continued exploration of new scanning technologies may not be necessary.

3.2 Image pre-processing

Archival images often suffer from low contrast and brightness levels, which may stem from errors during acquisition or digitization (Farella et al., 2022b; Knuth et al., 2023). Consequently, research in this domain has increasingly proposed the use of radiometric equalization and image enhancement to mitigate these deficiencies. The primary aim of such studies is to apply image enhancement techniques during the preprocessing stage to emphasize significant image features by adjusting pixel intensity values.

Lelégard et al. (2020) critique such conventional correction methods as Wallis filtering for their considerable limitations, despite their widespread use. They propose an alternative approach that incorporates Principal Component Analysis (PCA) to augment the results of Wallis filtering, yielding improved visual quality, even if applicable only to panchromatic images. Maurya et al. (2022) highlight the challenge posed by inadequate lighting during image capture, noting significant contrast and brightness variations in images from adjacent strips. To address this, they introduce an image enhancement strategy employing the Cuckoo Search optimization algorithm. This method produces two images – one with enhanced sharpness and contrast and another emphasizing brightness and clarity – subsequently merged through fusion to create the desired final image blending contrast and brightness.

Geometric calibration is crucial for preprocessing datasets that lack camera metrics, often involving fiducial marks for geometric transformation. Gonçalves (2016) applies a manual affine transformation based on fiducial mark positioning, albeit at the cost of increased processing time. Conversely, Salach (2017) proposes the introduction of SAPC (Scanned Aerial Photographs Correction), automatic software that resamples scanned analogue images using reference fiducial marks, ensuring consistent focal point positioning and resolution across images while eliminating black frames. SAPC also generates a binary image file to mask reference mark areas, enhancing preprocessing quality and facilitating block orientation for SfM technology applications, improving the scanned analogue photo quality in SfM processes (Feurer and Vinatier, 2018).

Redweik et al. (2009) demonstrate radiometric optimization using a Portuguese aerial photo collection, with the use of Contrast-Limited Adaptive Histogram Equalization (CLAHE) and the RADCOR algorithm to enhance image contrast. The latter, based on the Wallis filter, proves effective in enhancing images with haze, while removing non-uniform brightness through morphological image opening, which results in enhanced radiometric alignment and retained detail. Stark et al. (2022) note the effects of file format and compression on subsequent processing stages. They recommend using the TIFF format for analogue aerial photographs to avoid potential compression-related issues, even in the cases of nearly lossfree JPEG compression, which may still compromise SfM-MVS processing.

3.3 Aerial triangulation and geo-referencing

Researchers often underscore the underuse of archival aerial photographs in earth sciences, primarily due to challenges in geolocating these images precisely. A significant obstacle in pinpointing historical data accurately lies in the reliance on Ground Control Points (GCPs), a process noted in various studies (e.g. Meixner, 2019; Pinto et al., 2019) for its labor-intensive and complex nature. Achieving appropriate, accurate, and efficient georeferencing is recognised as a global objective among researchers, crucial for conducting quantitative and qualitative analyses and generating such essential products as the DSM or orthophotos from historical images. Establishing precise reference points is pivotal for generating time-based analyses and integrating data within Geographic Information Systems (GIS). Reference coordinates may be obtained through field measurements (Salach, 2017) or digital reference materials like road vector data or orthophotos (Mölg and Bolch, 2017), with the field survey and point measurement being the most time-intensive processing steps. The challenge of orienting photographs accurately often arises from the lack of camera information, complicating internal orientation reconstruction. Recent advancements have introduced applications based on mathematical modelling which are capable of correcting these distortions through self-calibration, which crucial for determining camera parameters when unknown (Aguilar et al., 2012). Precision in data triangulation is significantly influenced by the self-calibration method and the number of GCPs used.

Efforts to streamline, automate, and expedite image georeferencing have led to innovative approaches and research directions including strategies to reduce the reliance on numerous GCPs through geostatistical methods (Persia et al., 2020), co-registration on stable surfaces (e.g. Knuth et al., 2023), or linear features (e.g. Cléri et al., 2014), and employing SIFT descriptors to identify tie points (TPs) across varying data epochs (e.g. Faure et al., 2018; Giordano and Bris, 2019; Karwel and Markiewicz, 2022; Zhang et al., 2021). Other spatial data – such as LiDAR data (e.g. Korpela, 2006) are also used to orient archival aerial photos.

Cléri et al. (2014) introduced a technique aligning scanned analogue photos individually with line data from a topographic database, aiming for a precise photo orientation by extracting polylines from identifiable objects. Despite these efforts, the authors noted that desired quality standards still required improvement.

Craciun and Le Bris (2022) introduced an innovative method of orienting photos that depict areas lacking distinct features and textures using automatic georeferencing of historical images through the extraction and matching of 2D patches and 3D patch-based local alignment. By identifying sets of 3D patch matches and their corresponding 3D rigid transformations, this technique presents a promising solution for georeferencing images depicting rural landscapes.

Clasical acquisition of historical aerial data (aerial grid block) generally fails to meet the requirements of SfM algorithms. Flights were mainly performed with 60% sidelap and 20% endlap, while the SfM method requires overlaps exceeding 80% and 60% for sidelap and endlap, respectively (Feurer and Vinatier, 2018). Autocalibrating the camera without known initial values due to high acquisition ceilings and varied terrain can also complicate the process further when the data only come from images. For this reason, human intervention and knowledge are required when using the SfM algorithm. To eliminate input errors, approximate photo positions (coarse raid plan) are often defined (Zhang et al., 2020) so that the algorithm can conduct a more effective search for points between adjacent photos, whose already low radiometric quality is often problematic when searching for tie points. Despite these numerous challenges, the application of SfM has become essential to analyzing archival collections, particularly in examining aerial photographs (Hong and Roosevelt, 2023; Le Bris, 2022; Peppa et al., 2018; Stark et al., 2022). With the increasing popularity of the SfM method, recent years have witnessed numerous attempts to enhance its automation, which concentrate on refining specific steps or techniques within the SfM workflow to improve efficiency and accuracy.

Feurer and Vinatier (2018) explored an approach integrating SIFT extraction and matching techniques with the SfM-MVS framework adjustment methods. Additionally, Zhang et al. (2020) illustrated how combining traditional feature extraction with an advanced analysis can facilitate the reconstruction of three-dimensional structures from two-dimensional image sequences. Additionally, Zhang et al. (2021) introduced another processing stage designed to enhance image matcheswhich employs filtering mechanisms based on deep learning approaches, like SuperGlue, aimed at improving the selection of image pairs for matching. Neural network methods will also be more widely used to optimize this area of research. Recently, Maiwald et al. (2023) used the SuperGlue method and the DISK algorithm in an automatic method of orienting images. Both neural network methods are even more effective in helping to find the correct tie points which are used to geolocate the images spatially. One advantage of this method, which may prove very innovative, is that the algorithm can process photos almost devoid of textures.

Kim et al. (2010) introduced an innovative method for automatic georeferencing of archival images by employing the Harris Corner Detector for point detection across images from various periods. This complex process involves matching points through cross-correlation and filtering out inaccuracies using the RANSAC (Random sample consensus) algorithm, which applies a six-parameter transformation. The technique emphasizes identifying distinctive and persistent objects in images taken in different years, particularly highlighting human-made features like road networks and land plot boundaries.

Feurer and Vinatier (2018) engaged in similar feature search strategy by applying the SfM algorithm to a 170 km^2 test field, analyzing images from four surveys conducted over a space of 40 years. Building upon this concept, Giordano et al. (2018) developed the idea further by identifying and matching equivalent points between archival "coarse" ortho-images/DSMs and contemporary reference data. This study underscored the significance of a derived DSM in achieving full automation in the georeferencing process.

Karwel and Markiewicz (2022) presented a sophisticated extension of the SfM methodology, applying it to archival aerial photography, specifically focusing on images of Warsaw from 1986, 1994, and 2014. This research leveraged the SIFT algorithm to detect and match points across these historical images. The methodology is based on the SIFT algorithm for computer vision, enabling the identification and characterization of points that emerge as a unique, unambiguous, invariant, and stable set of photogrammetric control points following specific filtering techniques. The study involved a comparative analysis, comparing and contrasting the results derived from the SIFT algorithm with those obtained through the algorithms implemented in Agisoft Metashape, prominent commercial photogrammetry software. This comprehensive approach examines the efficacy and robustness of the SIFT algorithm in the context of archival image analysis and georeferencing.

The scholarly work by Heisig and Simmen (2021) introduces a highly automated photogrammetric workflow explicitly tailored to orient archival aerial photographs. This groundbreaking advencement is exemplified through an ambitious project aiming to develop aerial photos taken between 1985–1991, culminating in the creation of a comprehensive mosaic of Switzerland, covering the entire country. Drawing from a pool of 8,507 archival aerial photos captured at various scales, with an average Ground Sample Distance (GSD) ranging from 35 to 49 cm, this project successfully produced an orthomosaic with a pixel resolution of 50 cm.

Essentially, the study makes use of Catalyst, a commercial software module (formerly known as PCI Geomatics), which harnesses information on flight altitude, estimated principal point of the photo, and coordinates of the projection center in the field to automate the orientation process. Catalyst seamlessly generates TPs and locates GCPs by matching them to reference orthoimages/DTMs, drawing from reference data acquired from photos from 2014–2016 and a 2016 DTM. Despite the initial inaccuracy of automatic measurements, significant filtering enhances theaccuracy, leading the researchers to assert its efficiency to be 5–10 times greater than that of traditional methods, while maintaining a comparable level of quality.

The versatility and effectiveness of this methodology extend beyond Switzerland, as evidenced by its adoption in various projects and countries. Notably, this approach has been pivotal in modelling glaciers in Trentino, Italy (Poli et al., 2019), showcasing its adaptability to diverse geographical contexts. Furthermore, it has found application in Turkey for the orthorectification of extensive collections of archival images (Hong and Roosevelt, 2023), highlighting its broad applicability and relevance much beyond its initial case study.

A noteworthy instance of innovation comes from Zhang et al. (2021), who refined the SfM method by integrating feature search techniques with machine learning components. Their novel approach incorporates the SIFT and SuperGlue algorithms to identify TPs across images from different periods. This method is unique for its ability to operate without GCPs or a predefined flight plan, marking a significant advancement in terms of flexibility and applicability compared to conventional methods. By addressing challenges posed by scale differences, rotation, distortion, and evolving land cover effectively, this technique facilitates the detection of TPs across datasets from diverse temporal contexts, resulting in seamless georeferencing transfers between datasets.

Moreover, an auto-calibration process for the camera, which enhances the reliability of georeferencing, also forms part of this method. This calibration is validated through the computation of the Differential of DSMs (DoDs) from distinct datasets. The innovative pipeline has found successful application in a variety of studies, such as: landslide monitoring, urban expansion, land use changes, earthquake impacts, and glacier movements (Santangelo et al., 2022; Zhang et al., 2020).

Knuth et al. (2023) present a comprehensive application of the SfM method tailored specifically to the requirements posed by historical imagery, offering an alternative to conventional approaches that rely heavily on manual intervention at each stage. Their proposed Historical SfM (HSfM) method entails the combination of standard SfM technique with a self-calibration process for the camera. This novel approach involves a meticulous matching process to align an initial DSM derived from historical data with a contemporary reference DSM, crucial for rectifying positional, rotational, and, potentially, scaling inaccuracies originating from imprecise original camera placements without GCPs (Knuth, 2022).

Via this pioneering development, the generation of fundamental photogrammetric outputs from historical imagery, including point clouds and orthomosaics has been made possible. The process is capable of handling diverse collections of historical photographs. Initially, the method standardizes the photographs by identifying fiducial marks using pre-established patterns and calculating internal orientation parameters. Next, it identifies TPs and executes the SfM process. The aligned photographic block is then accurately georeferenced using both current and archival DSMs, with positions fine-tuned through Iterative Closest Point (ICP) co-registration. Systematic errors are mitigated further through camera parameter optimization with multi-temporal bundle adjustment. Crucially, as open-source, this method has been made accessible on GitHub, fostering widespread access and collaborative engagement.

3.4 Digital Surface Models

Aerial photography, known for its stereoscopic coverage, has long served as a valuable resource for terrain information. The advent of digital image processing techniques in the last century supplanted traditional manual methods for extracting point heights from these photographs. Recent advancements in dense image matching and SfM techniques coupled with MVS have revolutionized the generation of highly detailed point clouds, allowing for the intricate depiction of landscapes captured in these images. This transition to digital methodologies has popularized the creation of point clouds from photographs, particularly focusing on analyzing DSMs derived from historical and contemporary aerial photography.

Satellite data primarily operated in single-image mode, generating stereo pairs only upon specific requests, which limits their historical use. Another potential source of historical elevation data is radar interferometry, which has gained prominence, especially with the Shuttle Radar Topography Mission (SRTM) initiated in 2000 (Kurczyński, 2014). A further source of elevation data would seem to be Airborne Laser Scanning (ALS), but its relatively short history, has been able to make substantial contributions to elevation data collection only in the recent years. This is evidenced by Poland's extensive ALS data collection efforts from 2011 (Kurczyński and Bakuła, 2013). Traditional field measurements, the historical mainstay of survey methods, were only economically feasible for small areas, rendering them unsuitable for larger-scale research. Consequently, historical aerial photographs are unique due to their unique availability, coverage, and data accuracy regarding past landscape forms compared to other methods mentioned.

The DSM, serving as a 3D digital representation of a terrain's surface across a designated area, has fundamental importance in various spatial analysis and modelling applications in environmental sciences. It plays a pivotal role in comprehending long-term environmental changes and surface processes on Earth. Extensive exploration has been conducted for many years to create DSMs from photographic data and assess their precision (Pulighe and Fava, 2013). There have been numerous comparative studies of digital modelling techniques and LiDAR methods (Haala et al., 2010; Höhle and Höhle, 2009). The technique of automatic DSM extraction from aerial photos using stereoscopic matching emerged in the early 1990s, relying on feature-based matching (FBM) algorithms (Nebiker et al., 2014). Various software applications facilitate the reconstruction of dense DSMs using images, mainly applying the Semi-Global Matching (SGM) method, pioneered by Hirschmüller (2011). Despite their advantages, elevation models derived from imagery face challenges, particularly in urban and forested areas, necessitating automatic filtering and classification to distinguish ground data accurately (Höhle and Höhle, 2009).

The introduction of SfM-MVS techniques has significantly expanded the capabilities of the DSM generation. Ishiguro et al. (2016) conducted an in-depth analysis of DSMs produced from aerial photographs using SfM-MVS, revealing that their accuracy is comparable to the resolution of the aerial images used. They emphasized the cost-effectiveness and high precision of the data, validated against Global Navigation Satellite System (GNSS) reference data. Similarly, Mölg and Bolch (2017) demonstrated that SfM techniques can generate DSMs of similar quality to traditional photogrammetry methods, offering such advantages as denser point clouds and reduced noise, leading to a higher-resolution final DSM. Building upon these findings, Bakker and Lane (2017) showed that DSMs derived from SfM-MVS exhibit comparable characteristics to those obtained through conventional photogrammetry, even when processing archival images from decades ago. Gomez et al. (2015) conducted a comprehensive study of the use of SfM-MVS with historical aerial photographs for geomorphological and vegetation studies. Their research highlighted the promising potential of such data in reconstructing past environments and geomorphology. They demonstrated that even vegetation features, including tree heights, could be extracted and monitored over extended periods, opening new possibilities in biology and biogeography.

Ginzler and Hobi (2015) study represents a significant effort using historical aerial images to generate digital DSM surface models covering the entire territory of Switzerland. This initiative was motivated by the importance of surface models in understanding the three-dimensional structure of forests. The nationwide DSM creation process was largely automated, achieving a pixel resolution of one meter through photogrammetric dense image matching. Additionally, Canopy Height Models (CHMs) were derived from current Digital Terrain Models (DTMs). The accuracy of these DSMs and CHMs was verified using topographic field points and stereo measurements. The study successfully computed data for at least two periods across 81% of the national territory (Waser et al., 2015).

Pinto et al. (2019) emphasized the vital need for accurate DSMs in catalyzing the precise orthorectification of historical aerial photographs, a process that is essential for creating detailed land cover maps as well as various other applications. In regions characterized by significant elevation variations, the importance of a high-resolution DSM becomes even more pronounced. Osińska-Skotak et al. (2019) devaluated the quality of DSMs generated from historical aerial photos, focusing specifically on individual trees and densely-canopied groups. Their investigation examined how different threshold heights in elevation models influence the accuracy of mapping tree and shrub extents. Optimal results were observed at threshold heights ranging from 1.25 to 1.75 meters, determined based on the archival images under scrutiny. The researchers underscored the precision of point clouds generated through dense image matching, particularly in accurately representing the canopy's top surface. However, they also noted a limitation in these models, as they failed to provide measurements for under-canopy heights, thereby complicating precise assessments of tree height.

Grottoli et al. (2020) undertook an evaluation of various techniques aimed at refining depth maps and purifying point clouds using Agisoft Metashape Pro, to identify best practices for generating reliable DSMs. Their study involved a review of twelve DSMs derived from historical aerial photographs, comparing them with DSMs generated from LiDAR and UAV sources. Meanwhile, Santangelo et al. (2022) used DSMs derived from historical aerial photographs in a study area located in southern Italy, renowned for experiencing a slow-moving landslide since the 1950s. Their research aimed to assess the efficacy of these models in documenting morphological changes over time. They conducted a comparative analysis by examining variations in DSMs over time and correlating these with independently developed landslide maps, combining their expert knowledge and manual image analysis techniques.

3.5 Land cover from historical aerial images

Land cover characterization serves as a fundamental dataset crucial to a wide array of interdisciplinary scientific pursuits. The classification of Earth's surface features varies in terms of number, type, and definition, depending on the specific application and geographic scale of the study. While global initiatives, such as the Corine Land Cover (CLC), provide broad classifications encompassing categories including: urban areas, forests, water bodies, and agricultural lands, it is the region-specific projects, such as national topographic databases, that offer more localized and detailed classifications. These local-level analyses allow for the identification of specific features, for example, individual buildings, road types, and forest species, providing a finer granularity of information (Mallet and Le Bris, 2020).

Aerial imagery has long been a cornerstone in the study of land cover, particularly in the creation of topographic maps (Wójcik, 1991). Historically, land cover information was extracted through manual photo-interpretation techniques, while satellite imagery has also been employed to produce land cover maps, albeit with limitations in spatial resolution, which constrained the level of detail in classifications. Detailed historical land cover and land use maps, especially those delineating more than three classes prior to 1990, are scarce (Faure et al., 2018).

Satellite imagery, starting from the 1960s with grayscale CORONA satellite images and later with the Landsat program initiated in 1972, has been instrumental in documenting land cover changes. The early Landsat satellites offered a spatial resolution as coarse as eighty meters (Osińska-Skotak and Rączkowski, 2023). Despite the spatial limitations, satellite data have been frequently used for monitoring urban land cover changes, although challenges persist, including: low spatial resolution, limited temporal scope, and 2D information (Le Bris et al., 2020). Studies of the use of black and white images for creating archival land cover databases have been relatively limited in number. Meanwhile, advancements in digital image processing techniques, such as classification, have introduced a level of automation, making it feasible to use historical images for research purposes and thus reducing reliance on manual analysis (Caridade et al., 2008). For instance, Pinto et al. (2019) conducted a project using archival aerial photographs from 1947 to generate land cover maps, aiming to examine long-term socio-ecological trends. In their study, historical images were analyzed through visual interpretation by trained aerial interpreters to identify various land cover types, as the radiometric quality of the images was insufficient for automatic or semi-automatic techniques.

In a noteworthy endeavor to monitor landscape dynamics, Nebiker et al. (2014) employed methodologies involving digital image processing of historical photographs spanning up to half a century. They focused on object detection, particularly , identifying buildings, to delineate urban expansion patterns and analyze ensuing transformations. A pivotal aspect of their investigation entailed leveraging DSMs derived from these archival images via dense image-matching algorithms. This approach displayed remarkable levels of automation and precision, boasting detection rates of 92% for grayscale images dating back to 1959 and 94% for color images from 2007.

The advent of deep learning technologies has ushered in more sophisticated and efficient mechanisms for land cover mapping. These advanced methodologies demand a robust interdisciplinary foundation, bridging the realms of computer science and geography (Ratajczak et al., 2019a). Nonetheless, the imperative to document and comprehend the ever-evolving Earth's landscape propels researchers worldwide to actively engage in such scholarly pursuits. In a seminal exploration aimed at automating generating land cover databases, by leveraging expertise in geographic sciences, Ratajczak et al. (2019a) curated a comprehensive training dataset for their investigation, comprising 4.9 million labeled image segments. This dataset, dubbed HistAerial, is meticulously documented and encompasses eighty-one black-and-white aerial photographs captured between 1970 and 1990, categorizing seven primary land cover types. HistAerial has been made openly accessible to the research community. Furthermore, their methodological framework integrated low-level Rotated-Corner Local Binary Pattern (RCRLBP) texture filters. Their extensive inquiry encompassed a comparative analysis of state-of-the-art texture feature extraction and classification techniques, including deep Convolutional Neural Networks (CNNs).

Deep learning methodologies, particularly CNNs, emerge as the most adept strategies for semantic segmentation, providing access to an extensive and representative training dataset. The challenge of procuring adequate training data looms large as a critical bottleneck. Addressing this challenge, Le Bris et al. (2020) devised two iterations of the Decony-Net deep learning architecture, drawing inspiration from the functional principles underlying the U-Net architecture. Their approach to constructing the training dataset leveraged data obtained from contemporary topographic databases. Employing deep learning for semantic segmentation, their investigation successfully discerned historical land covers across five distinct categories.

Numerous studies have underscored the arduous endeavor of assembling reliable training data (Giordano et al., 2018; Mboga et al., 2020), a process that demands considerable time and incurs substantial budgetary allocations. In their investigation,Mboga et al. (2020) assumed a fully convolutional approach to generate land cover maps, introducing two distinct network architectures tailored to handle contextual information. One design leveraged convolutional layers devoid of downsampling, while the other amalgamated downsampling with upsampled convolutional layers reminiscent of the U-NET framework. These networks were meticulously fine-tuned to discern three primary land cover categories, achieving commendable accuracy rates exceeding 90% and 85% within their designated test regions. Expanding on their previous work, Mboga et al. (2021) devised a domain adaptation strategy aimed at increasing the trained network's adaptability across diverse image mosaics. Their investigation scrutinized two unsupervised domain adaptation methodologies, namely DANN and D-CORAL. The study outcomes indicated that while standalone unsupervised domain adaptation might not suffice to yield precise land cover maps, its integration with a modest amount of reference data could alleviate the labeling workload compared to conventional supervised learning paradigms.

3.6 The colorization of grayscale images

The incorporation of RGB values into individual pixels of monochromatic images is recognised as a pivotal technique for improving the effectiveness of various image processing endeavors, including data classification and object recognition. The significance of imparting color to historical grayscale materials extends beyond such domains as photogrammetry and aerial photography, also resonating within sectors like the film industry and specific medical fields. These domains have pioneered methodologies for infusing grayscale images with RGB hues, underscoring the broad appeal and utility of image colorization. The importance of color in augmenting the discernment and examination of features in aerial photography was noticed over six decades ago by Heller et al. (1964), whose research elucidated that foresters experienced a significant enhancement of up to 27% in identifying tree species when using RGB film in contrast to panchromatic photographs. A similar and likely even greater improvement can be expected for unsupervised land cover classification algorithms. The process of colorizing grayscale images involves attributing colors to the pixels of monochromatic images to enrich their visual portrayal. As discussed in several scholarly articles (Dias et al., 2020; Larsson et al., 2016), this field encompasses three primary methodologies:

- manual colorization,
- example-based colorization,
- deep learning-based colorization.

Amidst the plethora of methodologies, CNN-based approaches have emerged as a dominant force in the recent years, establishing themselves as the technique preferred by scholars in the field of image colorization. These techniques harness the capabilities of deep learning to address the inherent complexities of colorization, including the challenge posed by grayscale images where different colors may share identical intensity levels, thereby impeding traditional colorization methods. Seo et al. (2018) engage in the intricate task of automating the colorization process of aerial imagery, which showcases the multi-faceted influence of environmental factors encountered during image acquisition. These factors, encompassing variables like the angle of sunlight that dictates the length and dimensions of shadows, and seasonal fluctuations that induce shifts in vegetation hues, significantly contribute to the diverse array of colors captured in aerial photographs. This variability introduces another layer of complexity to predicting colors for grayscale images accurately. To address this, the authors propose a novel approach for colorizing grayscale aerial images, by a fusion of random forest regression and change detection methodologies. The essence of this method lies in predicting the color values of individual pixels by exploiting the correlation between the grayscale image under examination and a reference image possessing similar seasonal attributes and geographical location. However, the efficacy of this approach hinges upon the availability of suitable reference images that closely match the original grayscale images in terms of geographic locality and seasonal characteristics. This prerequisite poses a significant limitation, particularly in the context of archival datasets, where such reference images may be scarce or non-existent, thereby constraining the broader applicability of this method across a diverse spectrum of historical aerial photographs.

In a seminal exploration into grayscale image colorization, Ratajczak et al. (2019b) introduce an innovative unsupervised methodology aimed at enhancing the visual fidelity of images while facilitating the automatic classification of land use in historical aerial photographs. Processing aerial imagery captured in France between 1970 and 1990, this research employs Generative Adversarial Networks (GANs) to develop a fully automated colorization method that operates without supervision. Remarkably, navigating the absence of historically colored images for reference or auxiliary data, the authors demonstrate the capability of their algorithm to generate colorized images that not only streamline human analysis but also facilitate the automated classification of land use patterns.

In an important study by Dias et al. (2019), cutting-edge CNN techniques are harnessed to propose a novel W-Net architecture, which is meticulously crafted to execute semantic segmentation of images while simultaneously predicting pixel color values in grayscale aerial photographs. By amalgamating two U-Net architectures, first encoding semantic class information followed by decoding this information to predict colors, an elegant fusion of segmentation and colorization tasks in aerial imagery analysis is achieved. Through rigorous quantitative assessments and visual evaluations, the researchers demonstrated substantial success in both colorizing and segmenting aerial imagery. Subsequently, Ishii et al. (2021) explored deep learning methodologies used for colorizing historical aerial photographs in Japan. Focusing on panchromatic images portraying river basins, the study employed Neural Style Transfer (NST) to construct RGB orthomosaics across three datasets, each boasting a pixel resolution of 1 m. 60,000 tiles, measuring 100x100 pixels each, were extracted from these mosaics to train the CNN used in NST, representing six distinct land cover categories. Furthermore, the VGG16 (Visual Geometry Group) model was incorporated, with adjustments made to the number of frozen layers during the process. Evaluation of the trained models on grayscale images, originally RGB, revealed colorization of sufficiently high quality compared to the original RGB images. In a follow-up investigation, Tanaka et al. (2022) extended the groundwork by Ishii et al. (2021), juxtaposing two sophisticated deep learning methodologies: NST and CycleGAN. The CycleGAN model, trained with 8,000 tiles sized 256x256 pixels and covering ten land use categories, displayed remarkable efficiency attributed to its unsupervised learning approach. This stood in contrast to NST's reliance on 60,000 labeled images for transfer learning. Despite the significant variance in training data volume, both methodologies yielded outputs of comparable quality of their colorization work.

Poterek et al. (2020) made noteworthy advances in the research domain by introducing a colorization method employing a conditional GAN. This innovative approach features a generator structured akin to U-Net and a Patch GAN architecture for the discriminator. Additionally, the study scrutinized the impact of colorization on land cover classification accuracy, unveiling substantial enhancements when utilizing colored images over grayscale, with performance improvements of +6% and +17% for distinct datasets.

Meanwhile, Farella et al. (2022a) contribute significantly to the field with their introduction of the Hyper-U-NET architecture, a fusion of U-NET-like structures and HyperConnections tailored specifically for the colorization of historical black-and-white aerial images. Comparative analysis with five other open-access, deep-learning-based colorization methods evidences its efficacy. Moreover, the authors meticulously detail the development of this novel network along with the creation of a training dataset comprising approximately 10,000 color aerial images, both of which are openly accessible on GitHub. To evaluate its performance, original RGB images were converted to grayscale, and the colorization technique was applied, ensuring a comprehensive assessment alongside other methodologies.

Furthermore, Iizuka et al. (2016) devised a solution employing a CNN integrating a fusion layer, uniquely merging local and global insights to process images of any resolution effectively. Additionally, Zhang et al. (2016) and Larsson et al. (2016), constructed their approaches basing on the VGG network architecture, aiming to correlate color distribution with semantic context using multi-level abstract features. Similarly, Antic (2024) introduced the NoGAN technique, refining image-to-image GAN training for expedited training durations, while Su et al. (2020) presented a strategy leveraging an instance coloring network, capturing object-level details alongside a network analyzing the entire image.

4 Examples of the use of historical aerial photos

The utilization of historical aerial photography encompasses a myriad of domains across different scientific disciplines and societal impacts. Over the years, various scholars have documented substantial findings documenting human activity, economic landscapes, as well as environmental and climatic shifts. The multifaceted utility of aerial photographs extends to diverse fields including geological and geomorphological investigations, forestry practices, agricultural assessments, settlement area interpretations, and transportation route studies (Chilczuk and Ciołkosz, 1966).

4.1 Forest management and ecology

In forest management, archival aerial photographs hold significant relevance. Acquiring comprehensive knowledge about forest resources and structural configurations is paramount for effective management and conservation efforts (Honkavaara et al., 2013). While traditionally utilized for photo interpretation and qualitative analyses, modern advancements have empowered their integration into DSMs for quantifying various forest metrics (Pulkkinen et al., 2018) and documenting temporal changes (Price et al., 2020). Insights from archived aerial photographs serve as foundational elements in creating national databases and generating CHMs (Ginzler and Hobi, 2015; Marty et al., 2022). Moreover, their efficacy in producing accurate forest cover maps and delineating key characteristics surpasses that of alternative methodologies (Waser et al., 2015).

Photogrammetric methodologies coupled with archival imagery play pivotal roles in forest inventory assessments (Myklebust and Groesz, 2019) and evaluating the extent of damage inflicted by past natural calamities such as windstorms or wildfires, or pest infestations (Lydersen and Collins, 2018). The extensive acquisition of aerial photos in bygone eras facilitates investigations into the rate of change within damaged or degraded areas. A prevalent concern in forest management, beyond human control, is secondary succession, which precipitates biodiversity decline and habitat degradation (Kupidura et al., 2019; Wężyk and Matyja, 2007). By leveraging archival data, the historical distribution of trees and shrubs can be discerned, aiding in monitoring the conservation status of natural habitats and species, which is a mandate for all member states of the European Union (EU). In the context of new EU entrants like Poland (which joined the EU in 2004), archival aerial photographs prove instrumental in gauging the pace and dynamics of ecological transformations (Osińska-Skotak et al., 2019). The digitized interpretation of aerial photographs offers numerous advantages over manual methods, chiefly through its seamless integration with GIS. This digital approach finds applications across diverse ecosystems, including Finland's peatlands, facilitating comprehensive ecological analyses (Jauhiainen et al., 2007).

4.2 Glaciology

The utilization of archival aerial imagery extends significantly into the domain of glaciology (Fleischer et al., 2023). Within this field, such materials serve as vital tools for monitoring glacier changes and understanding glacier dynamics (Mölg and Bolch, 2017). It is noteworthy that the Intergovernmental Panel on Climate Change (IPCC) has underscored the importance of glacial and periglacial systems as critical climate indicators, catalyzing heightened research interest in this area (Stark et al., 2022). Integration of aerial imagery with other datasets allows for precise detection of temporal discrepancies. However, processing data from distant epochs poses considerable challenges. In times when satellite imagery or LiDAR techniques were unavailable, expeditions were conducted over glaciers to procure images for manual stereographic measurements or to digitize glacier perimeters and extents (Poli et al., 2020).

These archival materials serve as foundational elements for automatic DSM generation and integration with diverse data sources. Owing to their capacity for both visual interpretation and metric analysis, scholars in glaciology esteem aerial photographs highly (Poli et al., 2019). Discrepancies between DSMs spanning different temporal epochs yield invaluable insights into local or glacier-wide surface elevation changes, including geodetic mass balance assessments (Mölg and Bolch, 2017). Photogrammetric techniques facilitate large-scale studies, as evidenced by Fieber et al. (2018), who conducted a detailed analysis of the heights and volumes of sixteen individual glaciers across four locations on the Antarctic Peninsula or Pasik et al. (2021), who used archival images to show deglaciation process in case of three glaciers using volumetric analysis with dense image matching involvement and interpretation of produced orthophoto.

However, the analysis of archival data for glacier studies often encounters complexity due to the poor radiometric quality of vast snow surfaces, characterized by extensive bright areas lacking texture and numerous shadows, particularly in mountainous regions (Micheletti et al., 2015). Such challenges historically hindered manual stereographic measurements. Despite these hurdles, archival aerial photographs remain a significantly more reliable source of information compared to traditional topographic maps. In certain cases, remote sensing analyses are complemented with geophysical techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR), providing a comprehensive spectrum of data for multivariate analyses (Cusicanqui et al., 2021).

4.3 Coastal hazards

Archival aerial photographs play a significant role in analyzing the evolution of marine hazards and risks, encompassing marine erosion, river erosion, and coastal monitoring (Grottoli et al., 2020; Redweik et al., 2016). These photographs offer a valuable historical perspective, facilitating the calculation of precise historical change rates and enabling forecasts regarding future shoreline positions. For instance, Appeaning Addo et al. (2008) used data acquired in multiple periods (1904, 1974, 1996, and 2002) to estimate shoreline changes and predict future trends for the next 250 years. Their analysis revealed an average land retreat rate of 1.13 meters per year, highlighting the significance of such assessments, particularly in the face of environmental threats like rapidly rising sea levels. This underscores the importance of adopting multi-criteria management approaches to threatened coastal areas (Miller et al., 2008).

Moreover, archival photogrammetric data are instrumental in determining volumetric changes along coastlines or within dune bands (Carvalho et al., 2020). Meanwhile, Bakker and Lane (2017) conducted an evaluation of the applicability of the SfM method to archival imagery, particularly focusing on quantifying river and floodplain morphology. Additionally, researchers are investigating the erosive impacts of river water and such infrastructure as dams on the surrounding environment (Aguiar et al., 2016).

4.4 Landslides

In addition to marine hazards, historical aerial photographs are vital for studying natural hazards, for example, landslides (Rault et al., 2020; Santangelo et al., 2022), which pose significant threats to both human lives and built environments, necessitating robust monitoring efforts (Rault et al., 2022). Accurate knowledge of landslide distribution is essential for developing effective planning and prevention strategies. Landslide inventory maps are often prepared through expert photointerpretation of historical aerial photographs, which offer invaluable insights into landscapes closer to natural conditions before significant anthropogenic pressures (Rault et al., 2019). The damage caused by landslides or mudslides includes destruction to farms and buildings, periodic blockages of roads and railways, and endangering human lives (Spalluto et al., 2021). Thus, the comprehensive analysis of archival aerial photographs plays a pivotal role in mitigating risks associated with natural hazards and enhancing disaster preparedness.

4.5 Urban development

Archival photographs play a crucial role in assessing the dynamics of urban development and the evolution of transportation networks. Dušánek et al. (2019) highlight their utility in creating orthoimagery and photorealistic 3D models to document changes in various local areas such as post-mining regions, military zones, mountain agriculture locales, and dam sites. Bozzini (2022) used archival images to analyze urban expansion patterns, shedding light on historical development trajectories. By harnessing digital orthophotos derived from historical images, researchers gain deeper insights into the evolution of rural settlements within socio-historical contexts (Hodač and Zemánková, 2018).

Moreover, historical aerial photographs serve as valuable resources for generating 3D city models spanning different periods, facilitating studies on urban development dynamics. Adami et al. (2015) exemplifies this with a study on Verona, wherein three distinct DSM models were created and compared across three time points (1954, 1981, 1997), elucidating urban growth patterns. Redecker (2008) illustrates how archival images contribute to the understanding of the redevelopment of former industrial sites and identifying potential environmental and health hazards. Similarly, Kuna (2022) and Meixner (2019) utilized archival photographs to produce orthophotomaps of Lublin and Prague, respectively, offering valuable insights into the historical spatial characteristics of these cities.

4.6 Cadastral surveying

Furthermore, archival aerial photographs are instrumental in delineating land use boundaries, agricultural practices, and cadastral changes (Cramer, 2022). The generation of digital orthophotos using historical aerial imagery allows for examinations of rural development trends over extended periods, as demonstrated by Hodač and Zemánková (2018) in their study spanning 80 years. These comprehensive analyses underscore the significance of archival aerial photographs in elucidating the historical trajectories of urban and rural landscapes, providing valuable data for research, planning, and decision-making processes.

4.7 Archeological artifacts

Archival photographs serve a diverse array of specialized purposes, including crucial tasks like unexploded ordnance detection, particularly utilizing images captured during World War II (Brenner et al., 2018; Karel, 2022; Kruse et al., 2019; Meixner and Eckstein, 2016). Despite the passage of more than 75 years, the remnants of unexploded bombs continue to pose a significant threat, with estimates suggesting that over 2.7 million tons of bombs were dropped across Europe during the conflict, and approximately 10% failed to detonate (Ozdemir and Remondino, 2019). Automatic detection methods, as described by Kruse (2019), offer promising directions for identifying bomb craters and assessing the likelihood of unexploded ordnance occurrence, demonstrating a success rate of up to 95% in rural areas.

In addition, aerial photographs captured over the past eight decades often serve as the sole record of topography and events that have been obliterated. As a case in point, Różycki et al. (2023) used such photographs to generate orthophotomaps of destroyed German extermination camps from World War II and reconstruct the site's topography for analysis and documentation.

Furthermore, archival photos have been indispensable in archaeological detection and research for many years (Cowley et al., 2013). These materials offer a unique opportunity for chronological landscape analyses and evolution assessments (Gomez et al., 2015; Sevara et al., 2018). Over recent decades, there has been a growing recognition of historical aerial photography's significance in discovering and documenting archaeological sites, both previously unknown and known ones, and in characterizing broader cultural landscapes (Cowley et al., 2013). Archaeologists use such records as vital components of the understanding of the past, particularly when integrated with changing landscape contexts and other data sources, with aerial photography, both historical and recent, being a crucial complementary tool. It is noteworthy that aerial photography has played a pivotal role in archaeological discoveries such as the Roman coastal defense system, including Hadrian's Wall, as well as archaeological explorations throughout Britain, as discussed by Davidson and Peppa (2019).

5 Conclusions and summary

Archival aerial photographs represent an underexploited resource, yet they harbor immense potential for research in urban development, land use change, and long-term environmental monitoring. These images provide high resolution at frequent acquisition intervals, facilitating the creation of precise digital models crucial for scientific investigations. However, automating the analysis of these historical photographs poses significant challenges, necessitating a closer examination of the obstacles and potential research directions. This review identifies advancements in technology, including modern digital photogrammetry tools, algorithms, and machine learning techniques that play a pivotal role in unlocking the full potential of aerial photographs. These advancements will render them more accessible and beneficial across a spectrum of scientific disciplines.

Precise georeferencing archival aerial photography is indispensable for researchers worldwide, serving as a cornerstone for both quantitative and qualitative analyses using historical photographs and facilitating the creation of such critical products as DSMs or orthophotos. Difficulties in accurately orienting images often stem from the absence of camera information, which impedes the reconstruction of interior orientation. In recent years, the advent of various applications offering mathematical modelling to rectify these distortions has been essential, particularly in determining camera parameters whenever unknown. The adoption of SfM techniques has become commonplace in archival collection studies, with ongoing efforts to enhance the automation of the SfM process, focusing on refining specific steps or techniques within its workflow to enhance both efficiency and accuracy. This transition towards digital methodologies has fueled the proliferation of point clouds derived from photographs, particularly in the domain of DSM analysis stemming from both historical and contemporary aerial photography.

Characterizing land cover using historical aerial imagery serves as a vital data repository for diverse scientific inquiries, facilitating the categorization of surface features across varying scales, from overarching global endeavors to localized initiatives. The integration of digital processing and deep learning, notably CNN algorithms, has markedly augmented the efficiency and precision of the land cover mapping exercise. The application of greyscale image coloring, particularly in the context of historical aerial photographs, significantly enhances the efficacy of various image processing tasks, including data classification and object recognition.

Historical aerial photographs are instrumental across a range of scientific disciplines and societal contexts, providing invaluable insights into human activities, economic shifts, environmental transformations, and climatic variations. Given that these photographs often represent the sole record of topographical features and events that may have been altered or lost over time, their value extends across diverse fields of research and analysis. Their comprehensive coverage and detailed documentation make them indispensable resources for understanding past landscapes and informing present-day decision-making processes.

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