Research on Cloud Control photogrammetry based on Time-series Archived Aerial Photos and Its Application in Urban Governance in Beijing

Xiaokun Zhu [1], Yingchun Tao [1], Huimin Tian [1], Mingce Xu [2], Yutao Guo [1], Han Fu [1]

[1] Bigdata Centre, Beijing Institute of Surveying and Mapping,No. 60, Nanlishi Road, Xicheng District, Beijing, 100045, P.R.China - 67690323@qq.com, taoyingchun@bism.cn, tianhuimin_0123@163.com, guoyutao@bism.cn, fhsysu2013@163.com

[2] Beijing SmartSpatio Technology,Da Cheng Era Center, No. 6, Da Cheng Road, Fengtai District, Beijing, 100141, P.R.China - xumingce@qq.com

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Abstract

This study applies cloud control photogrammetry to time-series archived aerial photos to support urban governance in Beijing. Addressing challenges such as missing ground control points, heterogeneous coordinate references, and non-digitized aerial triangulation results, the proposed method leverages existing basic geographic products (e.g., DOM, DEM) as dense control sources, enabling automated aerial triangulation and 3D reconstruction without field control points. The workflow includes control source selection and organization, image preprocessing, cloud control point and tie point matching, block adjustment, and time-series product generation. Three experimental applications are presented: (1) reconstruction of river course changes in the Beijing Municipal Administrative Center using KH satellite images (1961 – 1974) and 1996 DOM, yielding time-series DOM products meeting 1:50,000 scale accuracy; (2) detection of illegal self-built building additions via DSM differencing from ADS80 images (2016 – 2017), identifying one-to-three-story structures; (3) 3D real-scene modeling of the Grand Canal’s Tonghui River section from 1975 film photos and 2015 control data, revealing 40 years of urban transformation. Results demonstrate that cloud control photogrammetry ensures spatiotemporal consistency and enables quantifiable, multi-temporal 3D analysis for urban change detection, illegal construction monitoring, and cultural heritage preservation.

1. Introduction

Real-world 3D data products based on photogrammetry technology can present the urban landscape in a novel way, with strong realism, high geometric accuracy, and clear expression, thus offering clear advantages in urban panoramic browsing and measurement. Beijing is a renowned historical and cultural city with a long history. In recent years, Beijing has made remarkable achievements in urban governance, focusing on restoring the appearance of the old city, closing tailings, strictly prohibiting mining, and restoring the natural scenery of green water and clear mountains. Assessing the quality of urban governance requires not only planar images but also more measurable three dimensional (3D) data.

Since the 1970s, Beijing has periodically acquired aerial image data for updating the basic scale topographic maps of the city. These archived historical aerial photographs serve as excellent witnesses to the changes in Beijing. Based on these historical aerial images, we have produced and stored 4D products including Digital Orthophoto Map (DOM) , Digital Elevation Model (DEM), Digital Line Graphic (DLG) and Digital Raster Graphic (DRG). With the development of real-scene 3D technology, we can generate 3D results based on these archived original aerial photos (Wei et al., 2024; Zhu et al., 2020). However, due to the long time span, missing control point data, inconsistent coordinate systems, and non-digitized aerial triangulation data, these time-series historical data cannot be reused effectively. The "Cloud Control" photogrammetry method proposed by the team led by Academician Zuxun Zhang of Wuhan University utilizes image matching technology to automatically obtain a large amount of dense control points from existing reference geographic information data (Zhang et al., 2017). Because the obtained control points are very dense, they form a control point cloud, hence the name "cloud control". We attempt to carry out cloud control photogrammetry with time-series aerial photos, achieving intelligent processing and 3D reconstruction of time-series archived historical aerial photos, providing a reference for subsequent urban governance and applications in Beijing.

2. Methodology

Cloud control photogrammetry technology can be applied to various types of imagery or video data, including aerial, satellite, and ground-based data. Among them, satellite cloud control photogrammetry based on DOM and DEM has been widely integrated into various commercial softwares (Sun et al., 2019). Currently, cloud control photogrammetry with multimodal data, including LiDAR point clouds, images and vectors, is gradually becoming a research hotspot. Due to its characteristic of not relying on field image control points, it is being used in tasks such as mapping uninhabited areas.

2.1 Workflow

In this research, the processing technology of cloud control photogrammetry is discussed, utilizing time-series historical aerial photos including scanned film images and digital photos in Beijing. It will cover key technologies such as selection and organization of control source data, preprocessing and organization of aerial photos, cloud control aerial triangulation (AT), time-series result production and urban governance application. The workflow chart is shown in Figure 1.

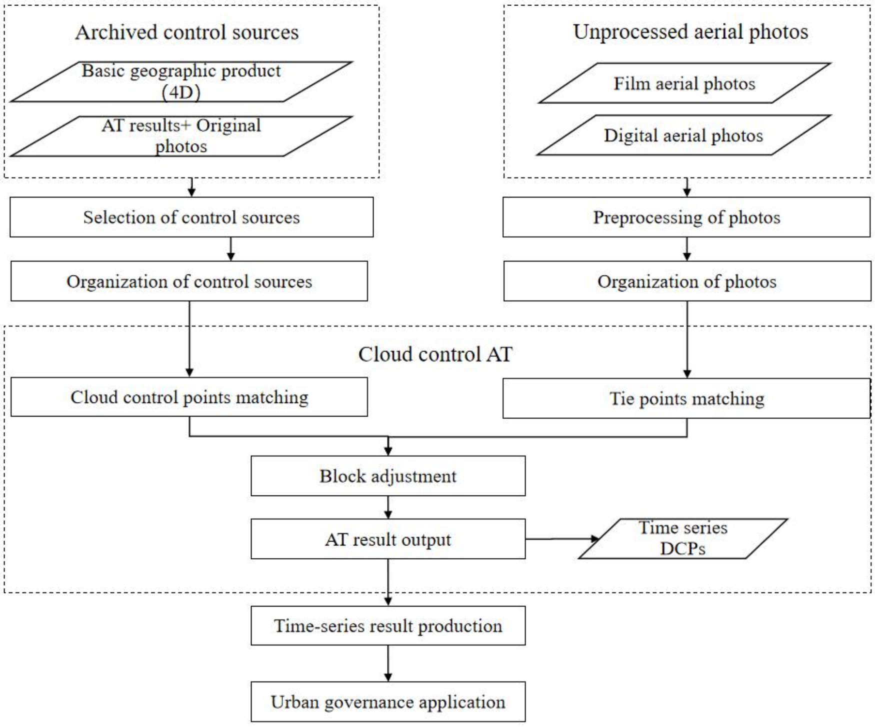


Figure 1. Workflow chart.

2.2 Method

2.2.1 Selection of control sources: Basic geographic products including traditional aerial 4D and original aerial photos with AT results, as archived data, could be selected as control sources for cloud control photogrammetry. For the aerial photos, basic geographic products are typically utilized for creating medium- and small-scale outputs, whereas original photos incorporating AT results are predominantly employed for producing high-precision, large-scale outputs. As a control source, the most prevalent combination is DOM and DEM. Regardless of the choice of control source, it must encompass the entire area of the images to be processed, with an accuracy level that should not fall below the precision requirements specified for the processed image outputs. Concerning spatiotemporal reference, the control source should be selected such that its temporal phase closely matches that of the images to be processed, and the spatiotemporal reference framework should remain consistent with that of the processed image outputs.

2.2.2 Organization of control sources: It is essential to gather control source data, relevant metadata, index diagrams or joint tables, quality inspection reports, alongside all other pertinent documentation. To facilitate automated processing, the organization and storage of control sources should comply with unified data standards, covering aspects such as precision, coordinate systems, and storage formats. It is recommended to adopt a folder-based hierarchical structure for data organization and storage. Basic geographic control sources should be organized using standard tiling methods, while existing AT results should be categorized by survey area. Standard metadata for cloud control photogrammetric control sources can be generated to uniformly describe information such as control source names, acquisition times, resolutions, organizational methods, and spatial references (Zhu et al., 2025).

2.2.3 Preprocessing and organization of photos: time-series historical photos encompass two types: one is photos from satellite or aerial film camera, and the other is photos captured by digital aerial cameras after 2005. We need to scan and digitize the film images, and manually arrange the flight paths and perform interior orientation for images without positioning and orientation system (POS). The organizational data includes digital aerial photos, index maps or joint tables, camera parameters, etc. Photos captured by different sensors should be stored separately, whereas those consecutively captured by the same device should be grouped in the same folder. The data should be organized by sortie and lens, and renamed as per actual requirements to facilitate automated processing in cloud control photogrammetry.

2.2.4 Cloud control AT: Cloud control AT includes cloud control point matching, tie point matching, block adjustment, and AT result output.

1. **Cloud control points matching**. Perform cloud control point matching between the control sources and the photos to be processed. The cloud control points should be evenly distributed within the scope of the photos to be processed. The average spacing between cloud control points is usually not greater than 2000 pixels, and the requirements can be appropriately relaxed in areas with weak texture and significant changes. When the density and range of cloud control points cannot meet the needs, additional manual supplementary image control points could be appropriately added.

2. **Tie points matching**. Perform tie point matching between the photos to be processed. POS data could be utilized to perform aerial triangulation on the photos, solving for their initial interior and exterior orientation elements as well as the geographic coordinates of the tie points. The tie points should be evenly distributed within

the overlapping photo range, and the average spacing between tie points is usually not greater than 1000 pixels.

3. **Block adjustment and AT result output**. The unit weight mean square error is set to 1.0 pixel, and the tolerance limit is 3.0 pixels. To facilitate standardized management of control sources, it is advisable to convert aerial triangulation results serving as control sources into standard Digital Control Photos (DCPs, Zhang et al., 2023) according to unified standard requirements.

2.2.5 Time-series result production and urban governance application: The output results include time-series 4D standard products, real-scene 3D, etc. It is worth noting that time-series historical products, obtained through cloud control photogrammetry technology with reference to the same set of control sources, exhibit good spatiotemporal consistency and can be utilized for urban change and illegal activity monitoring, encompassing not only horizontal but also vertical dimensions.
By combining these standard products, several traditional GIS analysis methods could be utilized for urban governance, such as the DSM difference method and change detection based on DOM. Furthermore, through real-scene 3D visualization and comparative display, the effectiveness of urban governance can be intuitively and effectively demonstrated.

3. Experiments

3.1 Analysis Experiment of Urban Change based on Cloud Control Photogrammetry with KH and Aerial Images

To analyze the changes of river courses in the Beijing Municipal Administrative Center, the historical KH (Keyhole) satellite images from 1961, 1965, 1970, and 1974 with a resolution of 3m were obtained. The aerial DOM data with the scale of 1:10000 from 1996 were employed as control sources for cloud control photogrammetry.

The workflow chart for time-series processing is shown in Figure 2.

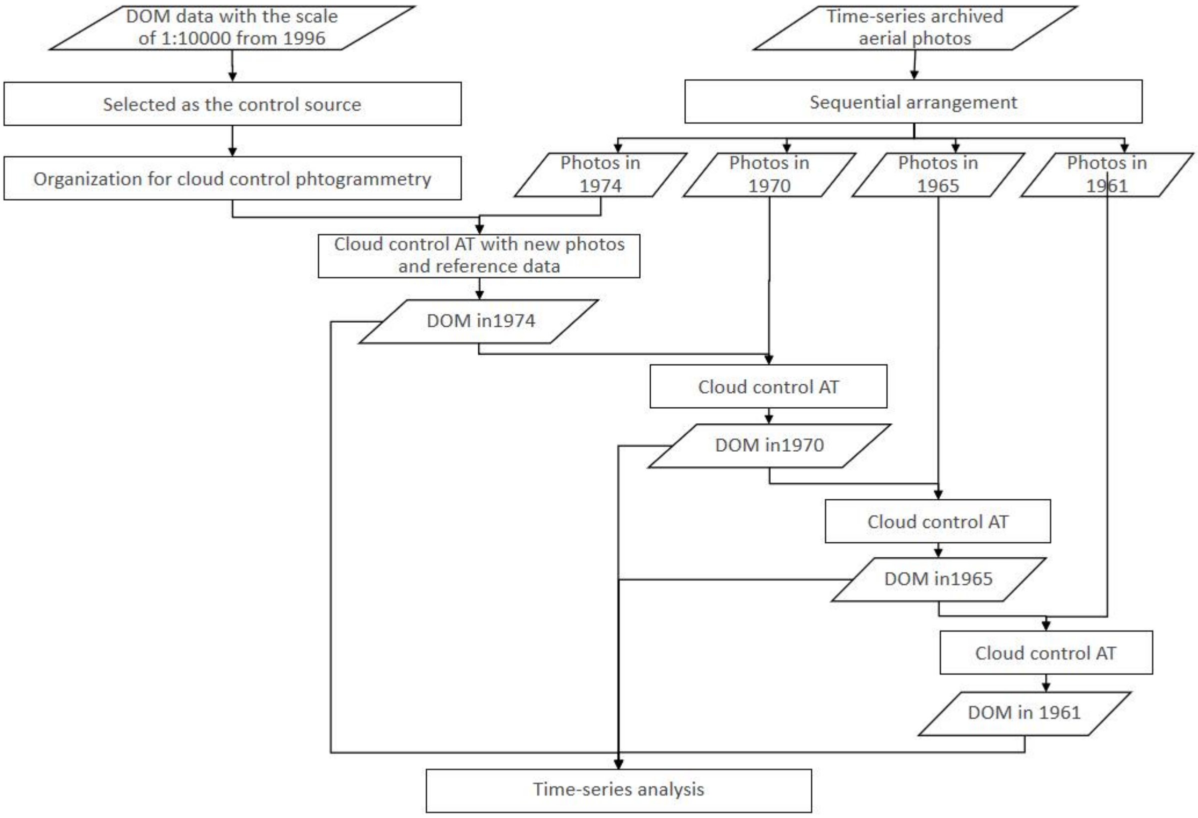


Figure 2. Workflow chart for time-series processing.

Considering 1974 and 1996 as the nearest years in sequence, we initially prioritized the selection of the 1974 KH imagery, utilizing the 1996 DOM as a reference, to perform cloud-controlled photogrammetry and subsequently generate the 1974 DOM results through orthorectification. Following this, we selected the 1970 imagery, referencing the 1974 DOM, to carry out cloud-controlled photogrammetry and produce the 1970 DOM results via orthorectification. This iterative process was continued to compile a temporal sequence of DOM imagery results.

The time-series DOM, produced after orthorectification, meets the standard product accuracy requirement of 1:50,000. The time-series DOM results, along with the DOM from 2019, are shown in Figure 3 below.


(a)

(b)

(c)

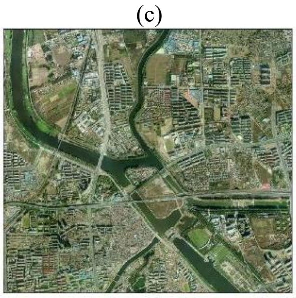
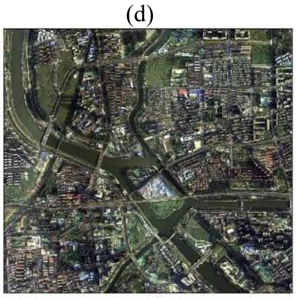
(d)

(e)

(f)

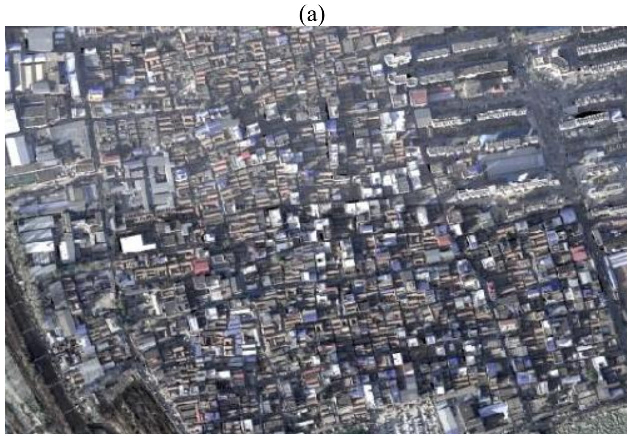
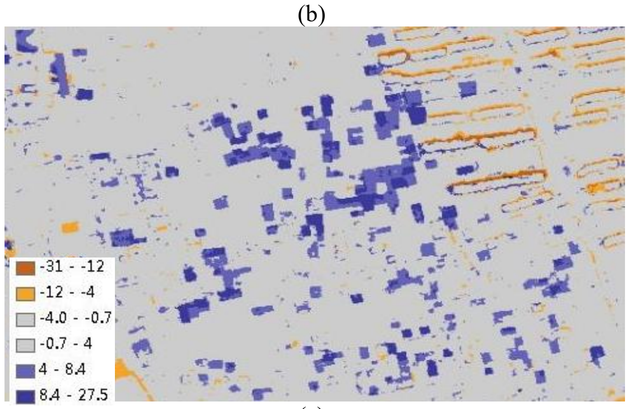
Figure 3. Time-series DOM for Five Rivers Confluence Area. (a)-(f) represent the DOM image results for the years 1961, 1965, 1970, 1974, 1996, and 2019, respectively.

The Five Rivers Confluence Area is located in the northwest corner of the sub-center of Beijing. It is formed by the confluence of the Wenyu River, Xiaozhong River, Tonghui River, North Grand Canal, and Yunchao Jian River. Since the Yuan Dynasty, this area has been managed for water control under the leadership of Guo Shoujing. During the Qing Dynasty's Qianlong period, the Yunchao Jian River was excavated, forming a system of joint management of five rivers. Since the 1960s, the modern water system pattern has gradually taken shape through flood control projects such as the Beiguan Flood Diversion Hub Project.

In 1960, the Beiguan Flood Retention Gate was built, and in 1963, the Yunchao Jian River Flood Diversion Gate was completed. In 2007, a source water island covering over 430 acres was formed, and in 2009, the official confluence of the five rivers was achieved through river channel renovation and after continuous ecological restoration, this area has become a habitat for over 30 species of birds. From Figure 3, through DOM image comparison, the process of river course changes from an I-shaped to a square-shaped intersection can be visually reproduced.

3.2 Analysis Experiment of Urban Self-built Buildings based on Cloud Control Photogrammetry with ADS80 Aerial Images

Beijing has carried out the investigation of safety hazards in self-built buildings, many of which are additions built on the original structures. To monitor these self-added structures, based on the ADS80 aerial photos and AT results from 2016, cloud control photogrammetry was employed to process the ADS80 aerial photos from 2017. The original imagery had a resolution of 0.2m. After processing, standard 0.2m DOM and 1m DSM results were generated, meeting the accuracy requirements of the 1:2000 standard through precision evaluation. Through DSM difference calculation, we can monitor the addition of structures to buildings. The following images show the two periods of imagery and the addition of structures discovered through DSM difference calculation.


(a)

(b)


(c)

Figure4. Time-series height change detection for urban self-built buildings. (a) and (b) are DOM results of 2016 and 2017, (c) is the DSM difference result.

In Figure 4(c), the blue patches represent additional houses, which can be seen to be generally one-story additions, with 13% being two- to three-story additions.

3.3 3D real-scene of Grand Canal’s Tonggui River Section based on Cloud Control Photogrammetry with Aerial Images Spanning 50 Years

The Beijing-Hangzhou Grand Canal originates in Beijing, traversing Tianjin, Hebei, Shandong, and Jiangsu provinces before terminating in Hangzhou, Zhejiang. Spanning a total length of 1,794 kilometers, it interconnects five major river systems: the Haihe, Yellow, Huaihe, Yangtze, and Qiantang rivers. The Beijing segment of the Grand Canal represents its northernmost reach, encompassing districts such as Changping, Haidian, Xicheng, Dongcheng, Chaoyang, Shunyi, and Tongzhou, with an overall length of 82 kilometers. On June 22, 2014, the Grand Canal of China was officially inscribed on the UNESCO World Heritage List, marking it as the seventh World Cultural Heritage site in Beijing. Notably, the Tongzhou section of the Tonghui River is included among the 40 designated heritage sites.

Utilizing the 2015 UCXP aerial imagery and AT results as the control source, and employing cloud control photogrammetry, we processed the 1975 RC-10 aerial film photos to create a time-series standard product of the real-world 3D landscape spanning four decades. This product offers a visual representation of the evolutionary changes in the river channel. Figure 5 presents a comparative analysis of the real-world 3D scenes.

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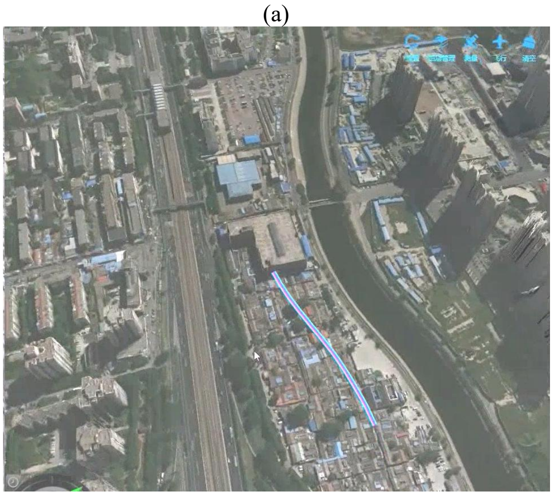
(a)



(b)

Figure 5. 3D modeling results for Tonghui River section of Grand Canal in (a) 1975 and (b) 2015 .

Through the comparison in Figure 5, we can observe the transformation of the canal from a natural river course to an artificially renovated shoreline after regulation. The areas on both sides have evolved from farmland and villages to towering skyscrapers today, providing firsthand historical data on the canal's changes during Beijing's 40-year urbanization process. For the protection of ancient villages, we use historical data to reconstruct the locations of the city walls and the architectural structures of houses from that time, serving as a reference for cultural relic restoration.

Conclusions

This research demonstrates that cloud control photogrammetry, when applied to time-series archived aerial photos, effectively overcomes the long-standing obstacles of missing control point data, inconsistent spatial reference systems, and non-digitized aerial triangulation information. By utilizing existing geographic products as dense cloud control points, the method facilitates intelligent, automated processing of historical film-based and digital aerial imagery. The Beijing case studies validate the capability to generate accurate time-series 4D products (DOM, DSM) and real-scene 3D models with quantifiable precision.

Furthermore, the approach reveals both horizontal and vertical urban dynamics over decades — exemplified by river course evolution, unauthorized building additions, and canal shoreline transformation — providing a robust and replicable framework for evidence-based urban governance. Future research should focus on integrating multimodal data (e.g., LiDAR point clouds, vector data) and standardizing Digital Control Photos (DCPs) to further enhance automation, scalability, and interoperability in long-term urban monitoring applications.

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References

Sun, Y., Zhang, L., Xu, B., Zhang, Y., 2019: Method and GCP -Independent Block Adjustment for ZY-3 Satellite Images. *Journal of Remote Sensing*, 23: 205-214. https://doi.org/10.11834/jrs.20198067.

Wei, B., Li, N., Ni, S., Zhang, Y., Wang, Y., Pan, C., Tang, X., Yang, F., Ding, R., 2024: A 3D reconstruction method for historical film aerial images:CN202111255960.9[P].[2024-07-31].

Zhang, Z., Duan, Y., Tao, P., 2023 :From Ground Control Point to Digital Control Photo. *Geomatics and Information Science of Wuhan University,* 48:1715-1723. https://doi.org/10.13203/j.whugis20230373.

Zhang, Z., Tao, P., 2017: An Overview on “Cloud Control” Photogrammetry in Big Data Era. *Acta Geodaetica et Cartographica Sinica*. 46:1238-1248. https://doi.org/10.11947/j.AGCS.2017.20170337.

Zhu, X., Pang, G., Chen, C., 2020: Research and Application of Historical 3D Modeling Based on Archived Non-Oblique Aerial Photos. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 43: 555-560.

https://doi.org/10.5194/isprs-archives-XLIII-B2-2020-555-2020.

Zhu, X., Liang, C., Tian, H., Xu, M., Guo, Y., 2025: Intelligent Processing Technology for Time-series Archived Historical Aerial Photos Based on Cloud Control Photogrammetry. *Sensors and Materials*, 37(4):1449-1458. https://doi.org/10.18494/SAM5302.