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UAV LiDAR mapping in the Historical Sanctuary of Machu Picchu: Challenges and Preliminary Results, Part 2

Mapowanie historycznego sanktuarium Machu Picchu przy użyciu bezzałogowego systemu powietrznego wyposażonego w LiDAR. Wyzwania i wstępne wyniki (cz. 2)

Keywords: LiDAR, UAV, Machu Picchu, architecture, archaeology.

Słowa kluczowe: LiDAR, bezzałogowy system powietrzny, Machu Picchu, architektura, archeologia.

Introduction: Results, discussion, and project challenges

Data from a UAV platform LiDAR survey produced many new observations. The research outline, data acquisition methods, and postprocessing were discussed in the first part of the study [Ćmielewski et al. 2021, pp. 159–170]. The results will be discussed separately for each site—the Chachabamba archaeological site and the Inkaraqay.

The Chachabamba archaeological site

The plans from the former excavations carried out by the Park's authorities [Ćmielewski et al. 2021, p. 162, Fig. 4] well documented Sector A—the central ceremonial section of the Chachabamba archaeological site [Bastante et al. 2020, pp. 289–304]. In the remaining sectors, since no extensive archaeological works had been carried out there, the approximate location of only a few wall and building relics was marked (Fig. 1). This created an excellent opportunity to choose the Chachabamba archaeological site for our UAV LiDAR system's pilot tests.

The LiDAR was used in Chachabamba for the first time in August 2018. The survey covered a strip along the left bank of the Vilcanota River, about 930 m long and 200–400 m wide. Following the principles already described [Ćmielewski et al. 2021, pp. 164–166], all the data were processed during winter 2018/19 in the back office at LabScan3D. The first attempts to filter the data and separate the points representing the ground surface (ground class) data did not bring the expect-

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Fig. 1. The Google Earth image of the Chachabamba site with previously known architectural relics marked in red; edited by J. Kościuk
Ryc. 1. Chachabamba na obrazie z Google Earth i dotychczas znane relikty architektury zaznaczone na czerwono; oprac. J. Kościuk

ed results. Even though the densities of the obtained ground class data reached a dozen points per square meter [Ćmielewski et al. 2021, p. 167, Table 2], and despite several attempts of using various visualization algorithms, the relics of the Inca walls known from the terrestrial survey did not appear from under the tree canopy. The situation was only improved by increasing the parameter for the extraction of points corresponding to the laser pulse's last reflection by an additional 0.5 m (ground class + 0.5 m). The density of the 3D point cloud then reached approximately 70 pts/m^2, and some of the relics sought became recognizable in the data visualizations (Fig. 2).

The results were further improved in post-processing by overlapping visualizations obtained in different modes: mainly multidirectional hillshade, local relief modeling, and sky-view factor. Particular images were loaded into Adobe Photoshop as separate layers and blended in multiple modes. This procedure allowed most of the hidden structures to be visualized (Fig. 2). The building relics being sought, roads and paths, watercourses supplying ritual baths, and features of the local topography that were difficult to recognize in areas overgrown by trees and bushes also appeared. These were both - relicts already known from the terrestrial survey and new discoveries, such as, for example, the three lines of east-west running walls in the southern part of Sector B. However, in most cases, a large discrepancy was noted between the relics' location resulting from the terrestrial survey and those from the LiDAR prospection. This can be explained by the problems in mapping these relics in the dense rainforest with conventional terrestrial survey methods. It

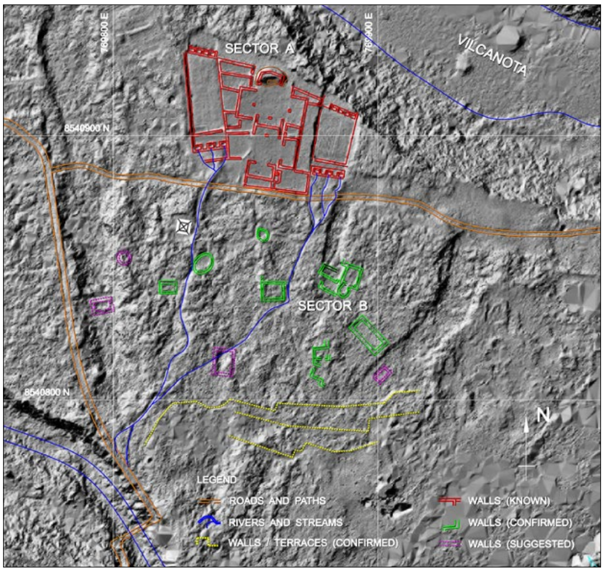

Fig. 2. Visualization and interpretation of LiDAR survey from Sectors A and B of the Chachabamba archaeological site; by J. Kościuk
Ryc. 2. Wizualizacja i interpretacja danych lidarowych z sektorów A i B w Chachabamba; Inwentaryzacja terenu. a – ortofotomapa centralnej części stanowiska archeologicznego Chachabamba; oprac. J. Kościuk

is difficult to find a clear line of sight when using a total station or achieve sufficient accuracy in GPS measurements under dense vegetation cover.

These results were verified on-site during the next fieldwork season in 2019. The detected relics' coordinates were extracted from ArcGIS software as SHP files and imported into Locus Map Pro running on a smartphone equipped with a built-in GPS sensor. Us-

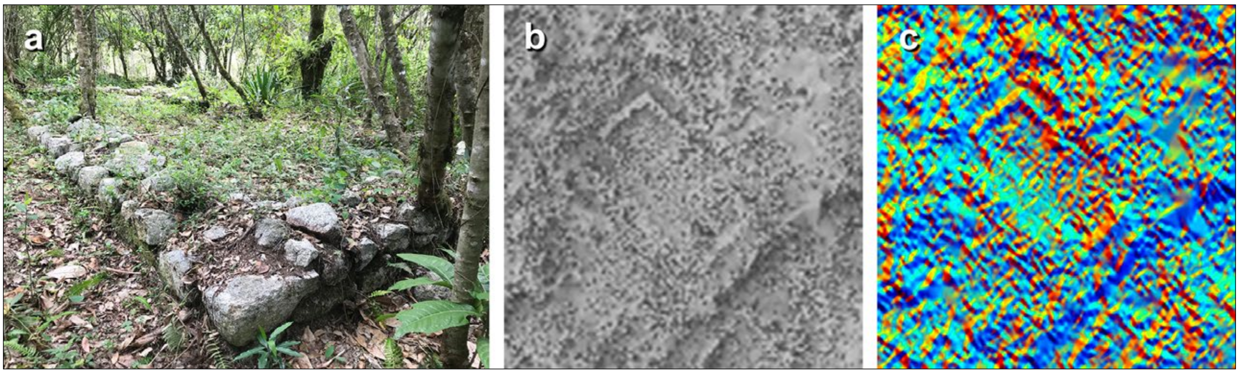

Fig. 3. An example of the relics of an Inca building (ca. 6.5 × 9.5 m; walls 0.9 m wide and less than 0.5 m high) detected in the LiDAR survey at Chachabamba; a – the current state of preservation, photo by D. Sieczkowska; b – visualizations of LiDAR data using the positive openness algorithm, elaborated by B. Ćmielewski; c – visualizations of LiDAR data using the multidirectional hillshading algorithm, by B. Ćmielewski

Ryc. 3. Przykład reliktów inkaskiego budynku (ok. 6,5 × 9,5 m; mur szer. 0,9 m i wys. poniżej 0,5 m) odkrytych dzięki pomiarom lidarowym w Chachabamba; a – aktualny stan zachowania, fot. D. Sieczkowska; b – wizualizacja danych lidarowych z wykorzystaniem algorytmu „positive openness", oprac. B. Ćmielewski; c – wizualizacja danych lidarowych z wykorzystaniem algorytmu wielokierunkowego cieniowania zbocza, oprac. B. Ćmielewski

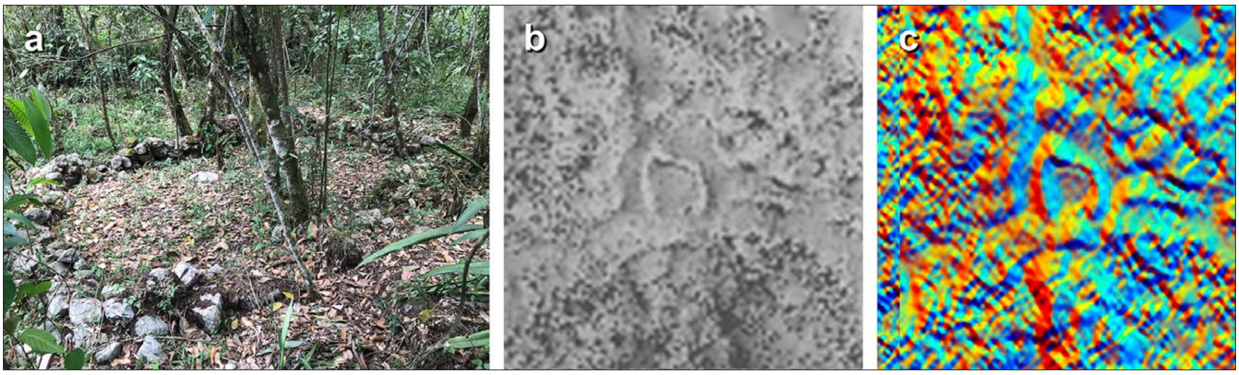

Fig. 4. An example of the relics of an Inca building (ca. 6.5 m in diameter; walls ca. 0.8 m wide and less than 0.4 m high) detected in the LiDAR survey at Chachabamba; a – the current state of preservation, photo by D. Sieczkowska); b – visualizations of LiDAR data using the positive openness algorithm, elaborated by B. Ćmielewski; c – visualizations of LiDAR data using the multidirectional hillshading algorithm, by B. Ćmielewski

Ryc. 4. Przykład reliktów inkaskiego budynku (średn. ok. 6,5 m; mur szer. 0,8 m i wys. poniżej 0,4 m) odkrytych dzięki pomiarom lidarowym w Chachabamba; a – aktualny stan zachowania, fot. D. Sieczkowska; b – wizualizacja danych lidarowych z wykorzystaniem algorytmu „positive openness", oprac. B. Ćmielewski; c – wizualizacja danych lidarowych z wykorzystaniem algorytmu wielokierunkowego cieniowania zbocza, oprac. B. Ćmielewski

ing this tool and navigating from one location to the other, it was possible to verify the LiDAR survey interpretation. They were correct in most cases (Fig. 3, 4).

Even though some of the walls had already been identified by the Machu Picchu National Archaeological Park's terrestrial surveys carried out in the 1990s, the LiDAR survey allowed us to define their actual extent more precisely. Also, the number of identified building relics has almost doubled.

Such an accumulation of architectural installations undoubtedly proves high building activity in this sector in Inca times. Based on this preliminary study, we can state that even if we consider this sector residential, it complemented the central ceremonial sector A and was probably inhabited by the people operating the ritual installations.

This research stage also resulted in an evaluation of the UAV LiDAR system and data analysis methods. The comparison between the interpretation of the LiDAR results and the field inspection was especially valuable. All these observations allowed a better preparation for the Inkaraqay archaeological site survey, where the topography was much more complicated, and the forest cover was much older than seventy years, as it was in Sector B in Chachabamba.

The Inkaraqay archaeological site and adjacent areas

The UAV LiDAR survey at the Inkaraqay archaeological site and neighboring areas took place during the 2019 season. Its main aim was to add as much as possible to the plan already prepared by the Machu Picchu National Archaeological Park's surveyors. Therefore, the study covered the area alongside the left bank of Vilcanota (ca 1,350 m × 350 m) between the Inkaraqay archaeological site and El Mirador de Inkaraqay (Fig. 5).

The interpretation procedure started with overlaying all the LiDAR survey deliverables onto the plan kindly provided by Jose Bastante, the Machu Picchu

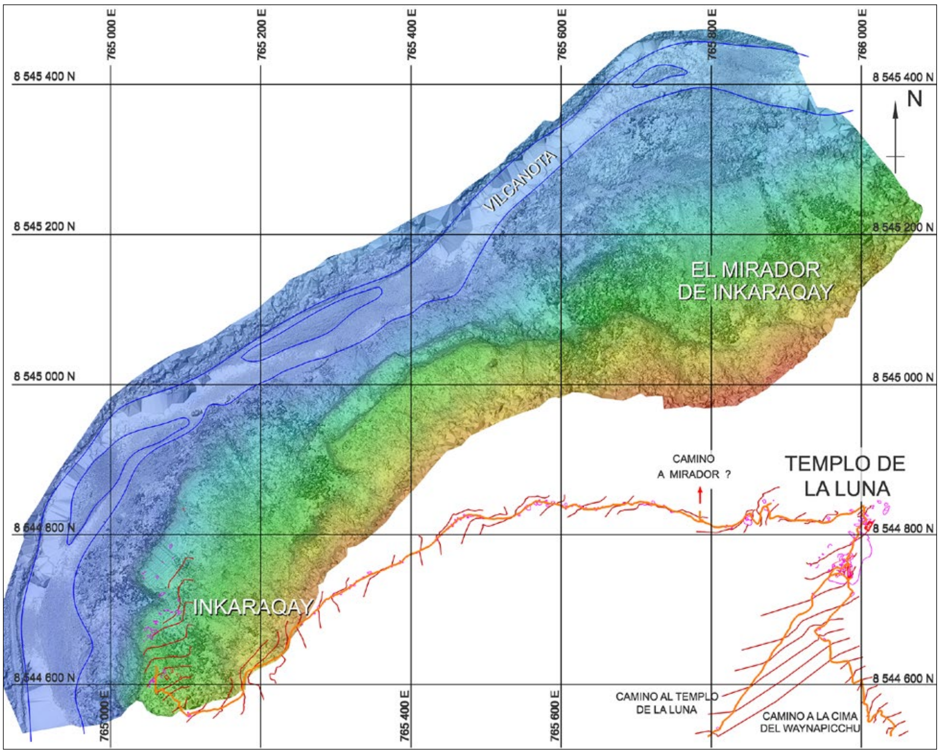

Fig. 5. The LiDAR survey's extent in Inkaraqay superimposed over the plan prepared by the Machu Picchu National Archaeological Park's surveyors; LiDAR data elaboration by B. Ćmielewski; edited and drawn by J. Kościuk

Ryc. 5. Zasięg lidarowych pomiarów w Inkaraqay na tle planu przygotowanego przez geodetów Narodowego Parku Archeologicznego Machu Picchu; przygotowanie danych lidarowych B. Ćmielewski; edycja J. Kościuk

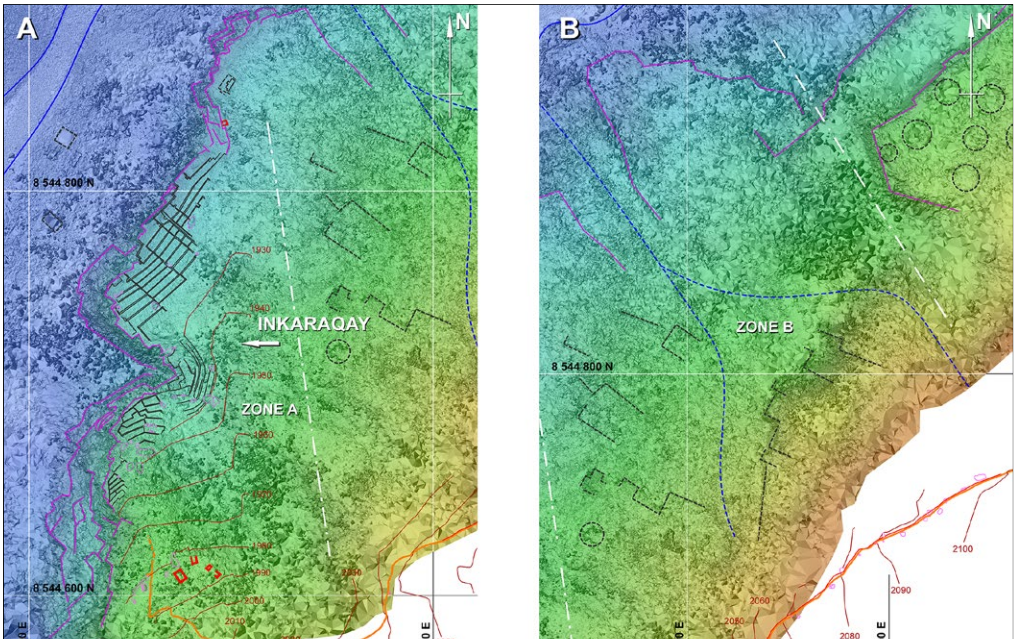

Fig. 6. Results of the LiDAR survey over the Inkaraqay archaeological site, A – Zone A; B – Zone B; LiDAR data processing by B. Ćmielewski; edited and drawn by J. Kościuk

a – Inca walls and buildings already mapped by the terrestrial survey; b – Inca paths known from the terrestrial survey; c – rock boulders; d – contour lines; e – walls and terraces recognized on LiDAR data; f – features of unrecognized character (terraces or sharp terrain faults); g – suggested Inca paths; h – rock cliffs' sharp edges; i – rivers and periodic streams; j – the contractual division between different zones

Ryc. 6. Wyniki pomiarów lidarowych nad stanowiskiem archeologicznym Inkaraqay, A – Strefa A; B – Strefa B; opracowanie danych LiDAR B. Ćmielewskiego; edycja J. Kościuk

a – mury i budynki inkaskie znane z prospekcji powierzchniowej; b – inkaskie drogi znane z prospekcji terenowej; c – głazy skalne; d – linie konturowe; e – ściany i tarasy rozpoznane na danych LiDAR; f – utwory o nierozpoznanym charakterze (tarasy lub ostre uskoki terenu); g – sugerowane drogi inkaskie; h – ostre krawędzie urwisk skalnych; i – rzeki i potoki okresowe; j – umowna granica stref

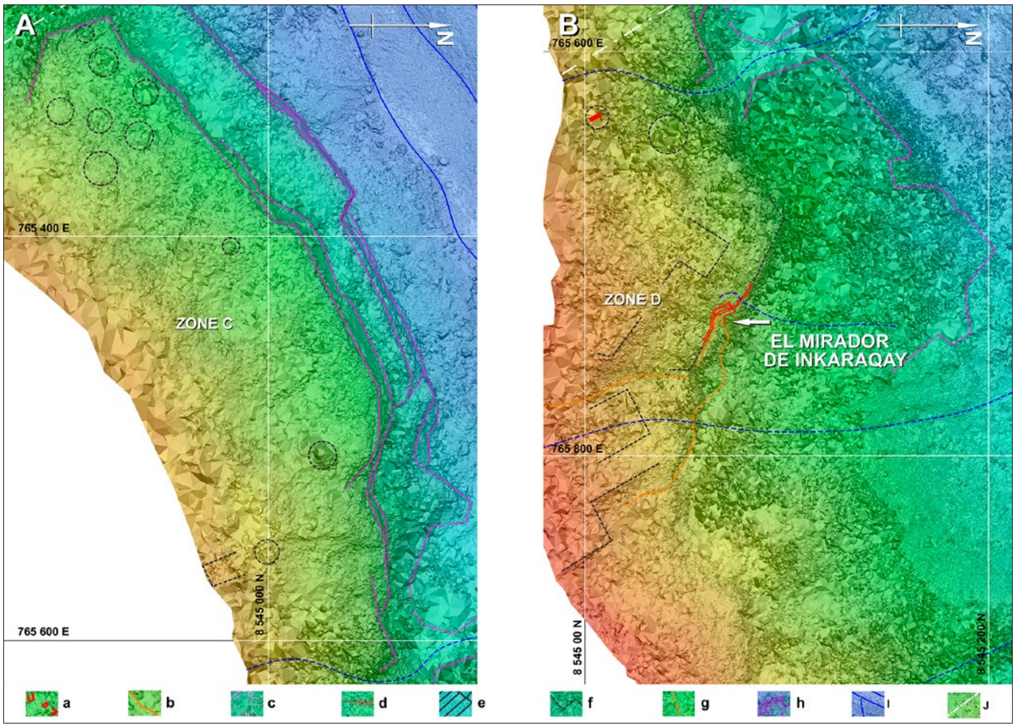

Fig. 7. Results of the LiDAR survey over the Inkaraqay archaeological site, A – Zone C; B – Zone D; LiDAR data processing by B. Ćmielewski; edited and drawn by J. Kościuk

a – Inca walls and buildings already mapped by the terrestrial survey; b – Inca paths known from the terrestrial survey; c – rock boulders; d – contour lines; e – walls and terraces recognized on LiDAR data; f – features of unrecognized character (terraces or sharp terrain faults); g – suggested Inca paths; h – rock cliffs' sharp edges; i – rivers and periodic streams; j – the contractual division between different zones

Ryc. 7. Wyniki pomiarów lidarowych nad stanowiskiem archeologicznym Inkaraqay, A – Strefa C; B – Strefa D; opracowanie danych LiDAR B. Ćmielewskiego; edycja J. Kościuk

a – mury i budynki inkaskie znane z prospekcji powierzchniowej; b – inkaskie drogi znane z prospekcji terenowej; c – głazy skalne; d – linie konturowe; e – ściany i tarasy rozpoznane na danych LiDAR; f – utwory o nierozpoznanym charakterze (tarasy lub ostre uskoki terenu); g – sugerowane drogi inkaskie; h – ostre krawędzie urwisk skalnych; i – rzeki i potoki okresowe; j – umowna granica stref

National Archaeological Park's director. The overlays (six altogether), representing different visualization modes of the LiDAR data, were then checked individually for any potentially anthropogenic nature anomalies. The results were marked separately on each examined layer and then compared. If the observations on successive layers were consistent, they were transferred to the final results layer.

The outcomes belong to four classes with varying degrees of interpretation credibility. Among these, there were walls (suggested and only a few confirmed), paths (of possible Inca origin), anomalies of a linear and orthogonal character (could be either terraces or natural rock formations), and, finally, anomalies of a nature difficult to determine—perhaps small, single buildings, perhaps larger rock boulders. These were marked on the interpretation plan with dotted-line circles. The detected features are irregularly distributed alongside the southern border of the LiDAR survey and can be grouped into four zones.

The westernmost Zone A (Fig. 6A) represents the Inkaraqay archaeological site's terraces that had already been mapped in 2012 by the Park's surveyors. This area is devoid of taller vegetation, and for obvious reasons, it was sharply reflected on the LiDAR pictures and showed high compliance with the Park plan. In Zone B (Fig. 6B), located slightly to the east, linear anomalies with an orthogonal alignment dominate. These could either be terraces or natural rock formations. Further to the northeast is an almost 35 m wide rock landslide ravine already heavily overgrown with trees, separating zones B and C from each other.

Regarding morphology, Zone C (Fig. 7A) consists of two terraces inclined to the north and extending from southwest to northeast for a distance of approximately 330 m. A cliff marks the northern border of both terraces. No anomalies associated with relics of human activity have been detected on the narrow, lower terrace. All the potential relics discovered are overwhelmingly grouped in the western part of the upper and much wider terrace. At this research stage, it is not easy to prejudge their nature. These could be fragments of walls, small buildings, or large rock boulders that project above the surrounding ground level. For this reason, all these anomalies are only marked on the map with symbolic dotted-line circles. On the other hand, it was a good sign is that the only relic in this area placed on the Park's topographic map was also visible on the LiDAR image. This small wall section is roughly in the center of the almost 45 m wide ravine that separates Zone C from the more westward Zone D.

The UAV LiDAR survey's results for Zone D (Fig. 7B), which is covered with dense forest and therefore challenging to penetrate directly, brought about a significant expansion in the terrain's knowledge. The first striking observation is that, unlike Zones A, B, and C, the slope inclines differently. The slope exposure changes by almost 90°: from the northwest to the northeast. Undoubtedly, this was decisive in choosing this very place for locating the Inca astronomical observatory, El Mirador de Inkaraqay, positioned for observations of the June solstice, which can be seen from here at an azimuth of approximately 58° [Astete et al. 2016/17, p. 13, Fig. 5].

An analysis of the precise relief of the terrain obtained after filtering the vegetation cover revealed another feature. In Zone D, there are numerous terrain faults with an orthogonal orientation. The El Mirador de Inkaraqay observatory was built at one of these natural rock faults. So far, by cutting back the densely growing jungle, it has been possible to record about 40 linear meters of the entire complex's front wall, less than 10 m of which belong to the observatory proper. The remaining part comprises two walls stretching in a northwest/southeast direction. Their only function seems to emphasize the natural rock fault to give the whole a more monumental character. Both walls may extend further for about 30 m to the northwest and another 12 m to the southeast, where the natural rock fault turns inwards and runs for another 15 or 20 m. The whole arrangement is in the shape of the letter "C." The front part, culminating in the centrally located observatory, would then be about 80 m long.

Using the LiDAR, a completely new image of the entire complex emerges—much more monumental than one would have previously assumed. Suppose, which is highly probable, that the slope on which the observatory is located was not covered with forest in Inca times, the entire site, as seen from the Vilcabamba Valley, must have made an impressive manifestation of power and might, as expressed through monumental forms of architecture and the natural landscape [Gavazzi 2020].

The UAV LiDAR survey at the Inkaraqay archaeological site and neighboring areas took place during the 2019 season. All the data evaluation was in Poland after the field season ended. Under normal conditions, the next step would be to load the results of the LiDAR survey into a portable GIS system and go into the field to validate the preliminary interpretation, particularly in Zones A, B, and C. Since the global pandemic deprived the authors of completing this critical step, the final verification is still a matter for the future.

The Inkaraqay archaeological site's research has shown that the UAV platform requires modifications and adaptation for flights beyond the visual line of sight (BVLOS). It is impossible to find a safe place in this area for taking off and landing a heavy multirotor UAV loaded with expensive equipment. Such a place should simultaneously provide direct visual control over the flight. For this reason, the area covered by the LiDAR survey of the Inkaraqay area was limited only to a narrow strip along the river where the drone's flight could be directly observed from gravel islets in the river mainstream. The higher parts of the Huayna Picchu slope were visually inaccessible to the operator.

The LiDAR system assembled in LabScan3D and the software developed for the kinematic data workflow met the technical specification assumptions. It was possible to obtain 3D point clouds with sufficient density and sharpness of the recorded details. The already mentioned recording of overhead power lines at Chachabamba was a good test for confirming the parameters obtained. Also, the commercial TerraScan software package performed well in filtering vegetation cover.

The post-processing, however, turned out to be the bottleneck. The software used to visualize LiDAR survey results could not process full-resolution 3D point cloud files, hence the need for 3D point cloud decimation and the consequent loss of some information. Skills for correct data interpretation are equally important. However, the only way to achieve these is by practically verifying results in the field and accumulating experience. Future projects for LiDAR survey applications will serve this purpose well.

Another critical issue is to determine the range of the proposed UAV LiDAR survey. The experience to date shows that this method is viable for small (up to a few square kilometers) forested areas distant from any airfields, where LiDAR mounted on an aircraft could be economically and logistically unjustified. The mean ground point density obtained is also essential, as the anomalies searched for are usually small, and the higher density increases filtering reliability. The density can easily be raised by using repetitive cross-survey flights. Once the UAV operator team is in the field, repeating the flight is only a matter of additional time and available batteries to power the drone and LiDAR.

Conclusions

Comparing the achieved results with recent studies in Belize [Thompson 2020] or Kuelap [VanValkenburgh et al. 2020], one should emphasize the fundamental difference between these archaeological sites and the area of Chachabamba or Inkaraqay. These differences concern not only the nature of the vegetation cover or local topography but, most of all, the size and nature of the anomalies sought.

For Belize, the smallest anomalies to be detected (Classic Maya house mounds) varied from 20 to 275 m^2 or between 20 and 40 m in diameter in the case of the household plazuela, and not less than 1.2 m in height [Thompson 2020, p. 13–16]. Even with such a low resolution as 1.1 ground points/m^2 [Ćmielewski et al. 2021, p. 167, Table 2], it still gives from several dozen to several thousand points for the anomaly sought.

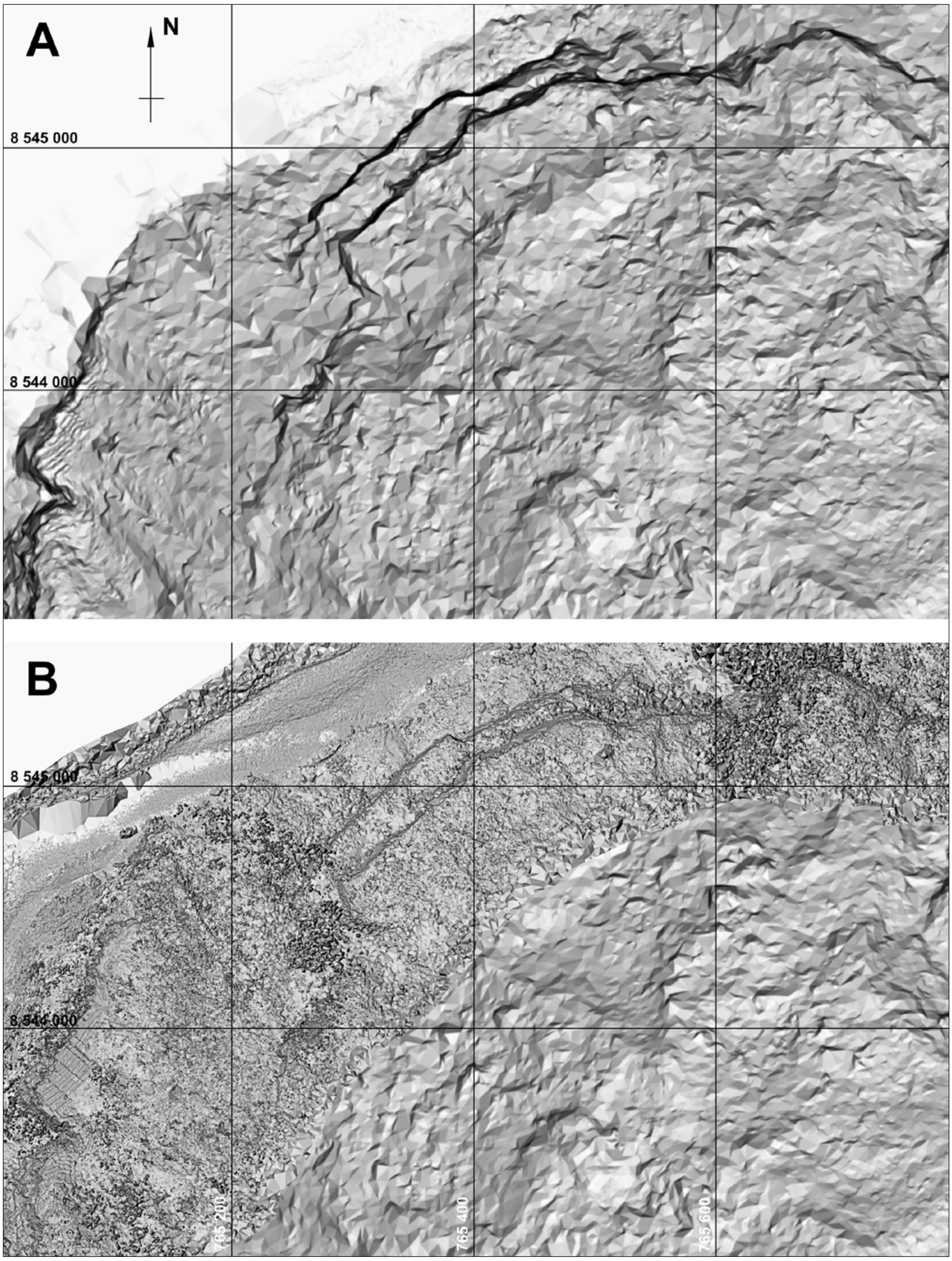

Fig. 8. The Inkaraqay archaeological site. Comparison of the results of long-range LiDAR scanning from a helicopter with the proposed UAV LiDAR system results; processing by B. Ćmielewski. A – long-range LiDAR results (ground points data only); data courtesy of DDC Cusco; B – same but with an overlay of UAV LiDAR system results (ground points data only)

Ryc. 8. Stanowisko archeologiczne Inkaraqay. Porównanie wyników skanowania LiDAR dalekiego zasięgu ze śmigłowca z wynikami proponowanego systemu UAV LiDAR; oprac. B. Ćmielewski. A – wyniki LiDAR dalekiego zasięgu (tylko dane z punktów na gruncie); dane dzięki uprzejmości DDC Cusco; B – to samo, ale z nałożonymi wynikami z systemu UAV LiDAR (tylko dane z punktów na gruncie)

In Kuelap, in turn, where the topography is more similar to that of Machu Picchu area, the detected relics of buildings are walls often preserved to a height of nearly 2 m, in most cases arranged in closed, oval shapes [VanValkenburgh et al. 2020, p. S82, Fig. 4, 5]. Thus, the medium size enclosures (ca. 5 m in diameter) result in about 40 m^2 of the preserved horizontal wall surface. Even assuming only 10 ground points/m^2, which is not too high for the UAV LiDAR system [Ćmielewski et al. 2021, p .167, Table 2], we will get at least several hundred return signals only from the wall's horizontal upper surface located higher than the surrounding area. Furthermore, this is not even counting the signals reflected from the vertical surfaces of the walls.

The relics of Inca walls preserved in Chachabamba are different. They represent mostly scattered fragments of walls hardly exceeding 5 m in length, preserved at the height of between one and two layers of stones (0.5 m on average). Such relics, with a wall thickness of less than one meter, give half as many return signals compared to the situation in Kuelap and many times less than in the case of platforms identified in Belize. The size and scattered character of Chachabamba relicts are much more difficult to isolate from the background signals.

Last but not least is the question of the quality and reliability of the obtained data. At this stage of the research, and after only two attempts at applying the LiDAR survey, it is too early to formulate general conclusions. However, with some caution, it can be stated that the results obtained at Chachabamba and Inkaraqay brought additional insight to understanding the character and function of both these archaeological sites.

In the case of Chachabamba, it was possible to detect additional relics and landscape features and determine the extent of the residential sector, which had only been assumed hypothetically. Although the close physical association between residential zones and ceremonial areas is a general characteristic of Inca sites in the region, knowing its extent helps plan and select priorities for further archaeological investigations.

The Inkaraqay archaeological site's LiDAR survey also produced some essential observations. The astronomical observatory location at El Mirador de Inkaraqay [Astete et al. 2016/17] was chosen for this part of the Huayna Picchu slope's specific orientation and characteristic features. It guaranteed the necessary observability of the June solstice sunrise over Yanantin peak on the other side of the Vilcanota river. Thanks to the skillful use of the exposed rocky cliffs, it also allowed for desirable monumental effects. It turns out that the observatory was not as isolated as it previously seemed. As a result of the LiDAR survey, several anomalies were detected between Inkaraqay and El Mirador that might be associated with Inca buildings' relics. This must still be verified by field inspection, which is planned as soon as pandemic restrictions are lifted.

The general conclusion drawn from this work is that for this type of research, surveying with a UAV platform equipped with LiDAR, GNSS, and IMU devices can be seen as a supplementary method to enrich data from aircraft-based long-range LiDARs [Kościuk, Ćmielewski 2022]. It allows for more detailed data collection in selected areas, limited to a few or a dozen square kilometers, when searching for the small relics of buildings hidden under the tree canopy, especially where the terrain makes it challenging to operate helicopters or planes. The Inkaraqay archaeological site is an excellent example of how the two technologies can complement each other by increasing the survey resolution in the areas of particular interest (Fig. 8).

It should be remembered that, as the experience in Belize shows, there is no universal method for analyzing and visualizing LiDAR data to identify archaeological features [Thompson 2020]. Each case, depending on the nature of the terrain and density of vegetation cover, and above all, on the nature of the anomalies sought (height, size, and geometrical shape, of archaeological features), requires the development of appropriate, most detective methods. These must still be worked out as more experiences are gathered at the Chachabamba and Inkraqay archaeological sites.

However, some challenges when flying UAV systems over remote archaeological sites in Peru, particularly in rainforest regions, will remain. The first is unpredictable weather and limited satellite visibility in narrow mountain valleys. Favorable weather conditions for flights (no rainfall, wind speed below 30 km/h) do not always coincide with the moments when an optimal number of satellites (at least six) is visible above the horizon [Kościuk, Ćmielewski 2022].

Finding places that will guarantee clear sightlines during the flight and, at the same time, safe taking off and landing might also be problematic. To this, one may add several restrictions concerning large-capacity lithium batteries, transportations and restrictions in entering the country with drones and high-tech sensors. Nevertheless, the authors are convinced that the use of LiDAR UAV systems to search for archaeological relics hidden under tree canopies has great potential. Along with the currently observed dynamic development of hardware and software, using LiDAR UAV systems will be even more popular in the coming years.

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Abstract

Besides the well-recognized central part, the National Archaeological Park of Machu Picchu encompasses approximately sixty lesser-known sites. Chachabamba and Inkaraqay are two examples. When using traditional field prospection on steep slopes covered by rainforest, it is challenging to detect traces of anthropogenic structures. A method that could help is the light detection and ranging (LiDAR) survey from airplanes or helicopters. The authors propose an alternative method using a self-developed LiDAR system mounted on a drone platform, able to detect even relicts of walls less than one meter high. This approach's main advantages are the speed and flexibility of prospection, high-resolution 3D point clouds, and the ability to penetrate the rainforest. The authors discussed data collecting methods, filtration, classification, and different visualization algorithms in the first part of the paper. The second part presents the preliminary results of the LiDAR survey over Chachabamba and Inkaraqay sites, the first validation of the outcomes, and general conclusions on UAV LiDAR feasibility in Peruvian rainforest conditions.

Streszczenie

Obok dobrze zbadanej centralnej części Narodowy Park Archeologiczny Machu Picchu obejmuje swoim zasięgiem także ponad 60 mniej znanych stanowisk. Chachabamba i Inkaraqay są tu dwoma przykładami. Na stromych, porośniętych gęstym lasem deszczowym zboczach tradycyjne metody prospekcji terenowej nie gwarantują wykrycia wszystkich struktur o antropogenicznym charakterze. Pomocne mogą tu być pomiary LiDAR (*light detection and ranging*) z pokładu samolotu lub helikoptera. Autorzy proponują alternatywną metodę z użyciem LiDAR'a zamontowanego na dronie, zdolnego do wykrywania reliktów murów o wysokości poniżej 1 m. Główne zalety tej metody to łatwość i prędkość prospekcji, wysoka gęstość chmur punktów 3D oraz zdolność do penetracji pokrywy leśnej. W pierwszej części artykułu przedstawiono metodę zbierania danych, filtracji i klasyfikacji oraz algorytmy wizualizacji wyników. Druga część artykułu zaprezentuje pierwsze wyniki pomiarów lidarowych w Chachabamba i Inkaraqay, wstępną ocenę uzyskanych rezultatów oraz możliwości zastosowania UAV LiDAR w warunkach peruwiańskiego lasu deszczowego.