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UAV LiDAR Mapping in the Historic Sanctuary of Machupicchu: Challenges and Preliminary Results: Part 1

Mapowanie Historycznego Sanktuarium Machupicchu przy użyciu bezzałogowego systemu powietrznego wyposażonego w LiDAR. Wyzwania i wstępne wyniki (cz. 1)

Keywords: LiDAR, UAV, Machupicchu, architecture, archaeology

Słowa kluczowe: LiDAR, bezzałogowy system powietrzny, Machupicchu, architektura, archeologia

Introduction

The following study is a part of a larger project aiming to analyze the archaeological sites' network within the Machu Picchu Archaeological Park. An additional goal was to define the extent of individual settlements and identify the types of buildings constituting their residential sectors. The Machupicchu National Archaeological Park, which covers 37,302 ha, was inscribed on the UNESCO World Heritage List in 1983. The name "Llaqta de Machupicchu" is the official term denoting the actual archaeological site, in which "Machupicchu" is written as one word.

A network of roads connects the llaqta of Machupicchu with numerous (ca. 60) smaller archaeological sites (Fig. 1). Only general locations and boundaries of these sites have been observed, but the degree to which they have been scientifically explored varies from site to site. Therefore, it can still be expected that in the less accessible areas of the Park, there are other, hitherto unidentified traces of Inca activity.

The project started in 2015, and its main objectives were oriented towards studying the function of two satellite sites: Chachabamba and El Mirador de Inkaraqay (Fig. 1). From an academic point of view, both of these sites look promising for at least two reasons.

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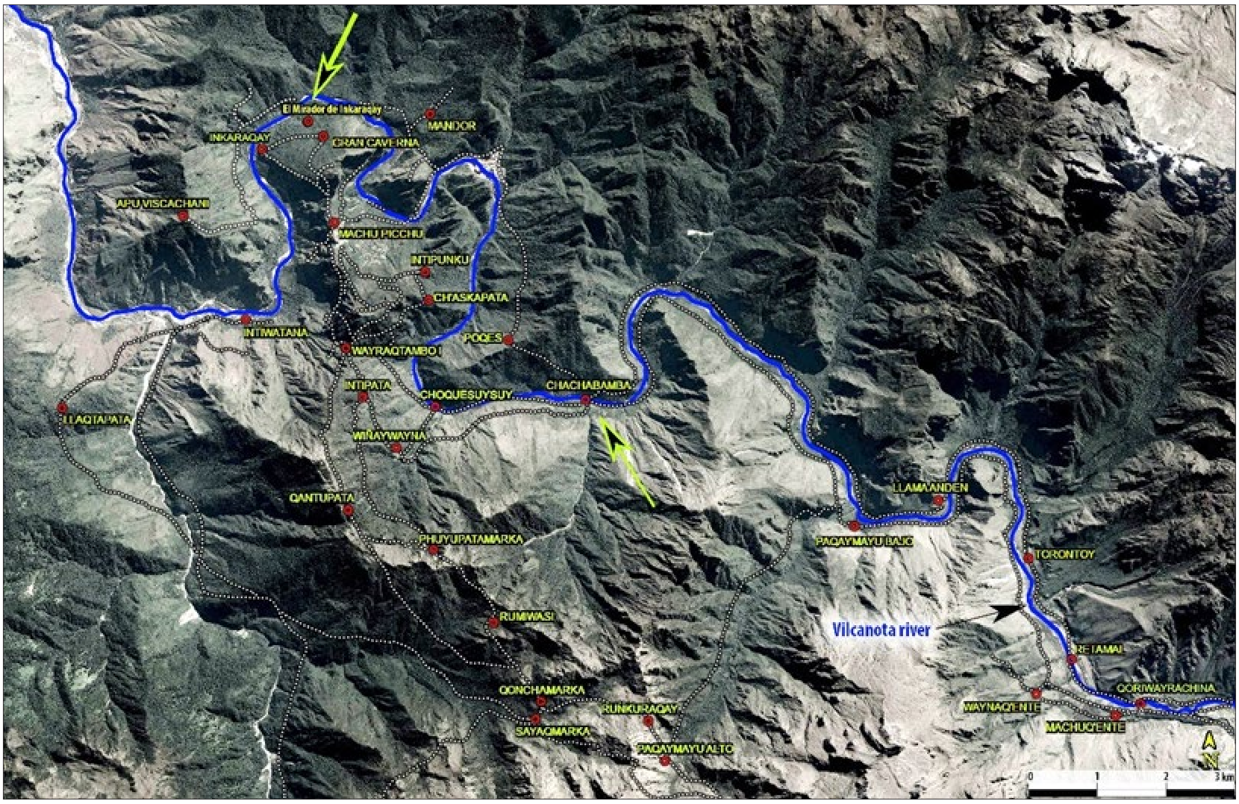

Fig. 1. Archaeological sites and Inca roads within the northern part of the National Park – Historic Sanctuary of Machu Picchu; by J. Kłaput.
Ryc. 1. Stanowiska archeologiczne i drogi inkaskie w północnej części Parku Narodowego – Historyczne Sanktuarium Machu Picchu; oprac. J. Kłaput.

Firstly, they are in the Vilcanota Valley, in an area that was a political, administrative, and religious center[1] associated with the Inka Pachacuti domain.[2] Secondly, both sites present an interesting example of the different phases of Inca activity in this region. In light of recently compiled radiocarbon dates,[3] the beginning of Chachabamba's construction coincided with that of the llaqta of Machupicchu. In turn, many factors seem to indicate that El Mirador de Inkaraqay belongs to the final phase of the Incas' activity in this area.[4]

The main problem related to such research is the complete recording of all of the area's natural and anthropogenic features. Since the central parts of both sites were not covered with dense vegetation, they could have been easily documented by digital photogrammetry (Fig. 2a) and terrestrial laser scanning (TLS) (Fig. 2b).[5] However, these central zones' study has not extended to the broader neighborhood due to the surrounding dense vegetation cover where some other pieces of evidence for Inca building activity are hidden. They often represent only relicts of walls that emerge from the ground by no more than two or three courses of stone blocks. Another factor are the technical and logistical problems of surveying very rugged areas covered by rainforest, which are difficult to access using traditional terrestrial exploration techniques. This situation inspired the idea of using aerial prospection with a LiDAR system mounted on a UAV.

In archaeological survey, aerial LiDAR technology has proven helpful in quickly mapping and acquiring data over large areas. However, its main disadvantages are the equipment's availability and the cost of bringing a specialized crew and equipment to the site.[6] Nevertheless, the aerial LiDAR technique occupies a special place in remote sensing for archaeological purposes, especially in densely forested areas.[7] The most famous and spectacular applications relate to research in Mesoamerica.[8] LiDAR survey also significantly impacted the understanding of the Angkor site in north western Cambodia.[9] Another example of research using a long-range LiDAR carried by helicopter are the recently published survey results of the Machupicchu National Archaeological Park.[10]

MATERIALS AND METHODS

Chachabamba archaeological site

Chachabamba (13°11'14.43" S; 72°30'34.26" W) is located, on the Vilcanota River's left bank, 104 km along the railroad leading from Cusco in the direction of Machupicchu Pueblo at an average altitude of 2,170 masl (Fig. 1). The first archaeological research at Chachabamba goes back to 1941, when Paul Fejos investigated the site.[11] During this work, most of the covering vegetation was cleared away, so the archival photographs document the buildings' conditions as the Inca had left them (Fig. 3). According to our present understanding, the site's character was mainly cere-

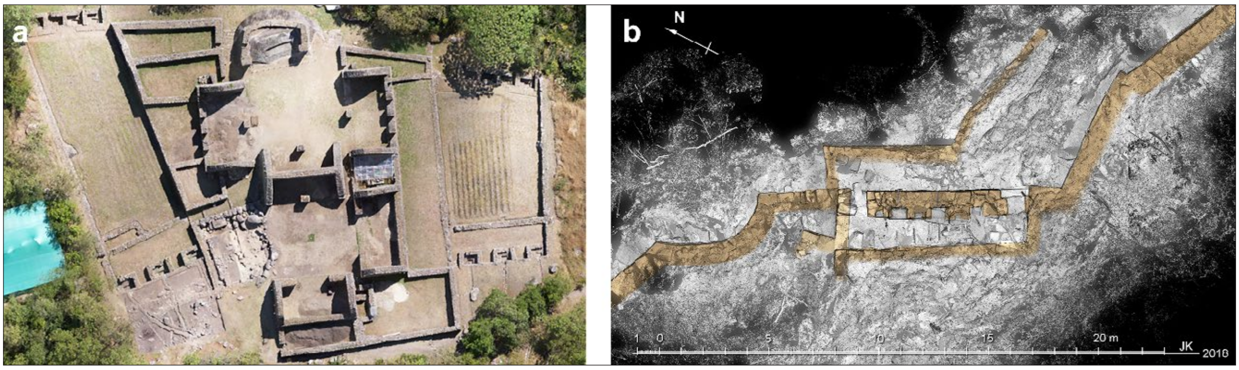

Fig. 2. Terrestrial survey. a – orthoimage of the Chachabamba archaeological site's central part; by B. Ćmielewski, b – El Mirador de Inkaraqay site on TLS survey; by J. Kościuk.
Ryc. 2. Inwentaryzacja terenu: a – ortofotomapa centralnej części stanowiska archeologicznego Chachabamba; oprac. B. Ćmielewski, b – stanowisko El Mirador de Inkaraqay na inwentaryzacji TLS; oprac. J. Kościuk.

monial, but some structures indicate also its residential and agrarian function.[12]

Further archaeological research at Chachabamba took place between 1996 and 1997. Current archaeological investigations started in 2016 and continue to this day within the research program of the Dirección Desconcentrada de Cultura Cusco, supported by the Center for Andean Studies of the University of Warsaw in Cusco (CEAC UV), with the help from the staff and equipment of the Laboratory of 3D Scanning and Modelling (LabScan3D) at the Wrocław University of Science and Technology.

Four different sectors can be distinguished within Chachabamba (Fig. 4). In the most thoroughly examined Sector A (ca. 3,500 m^2), the presence of a carved sacred rock and a system of fourteen fountains used for ablutions confirm its ritual function.[13] However, covered with very dense vegetation Sector B (ca. 8,500 m^2) of a predominately residential function (Fig. 5) was not examined in detail.[14] Even denser vegetation covers Sectors C (ca. 6,000 m^2) and D (ca. 9,000 m^2), where one can expect large terraces and some additional structures.

El Mirador de Inkaraqay and its relation to the Inkaraqay archaeological site

El Mirador de Inkaraqay (13°08'57.0" S; 72°32'55.0" W) is a small architectural structure situated on the northern slopes of Huayna Picchu on the left bank of

Fig. 3. Chachabamba during P. Fejos' expedition in 1941; courtesy of the Metropolitan Museum of Art, New York, Department of the Michael C. Rockefeller Wing.
Ryc. 3. Chachabamba w trakcie ekspedycji P. Fejosa; dzięki uprzejmości Metropolitalnego Muzeum Sztuki w Nowym Jorku, Wydział Skrzydła Michaela C. Rockefellera.

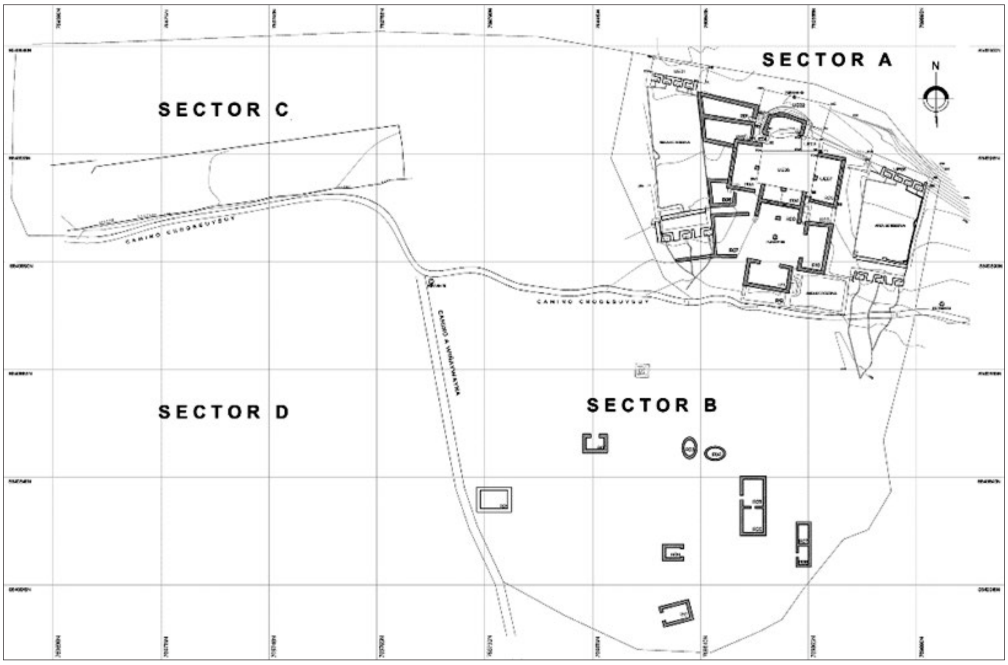

Fig. 4. Plan of the Chachabamba archaeological site, prepared by the Machupicchu National Archaeological Park's architects surveyors; courtesy of the DDC-Cusco.
Ryc. 4. Plan stanowiska archeologicznego Chachabamba, przygotowany przez architektów i geodetów Parku Archeologicznego Machupicchu; dzięki uprzejmości DDC-Cusco.

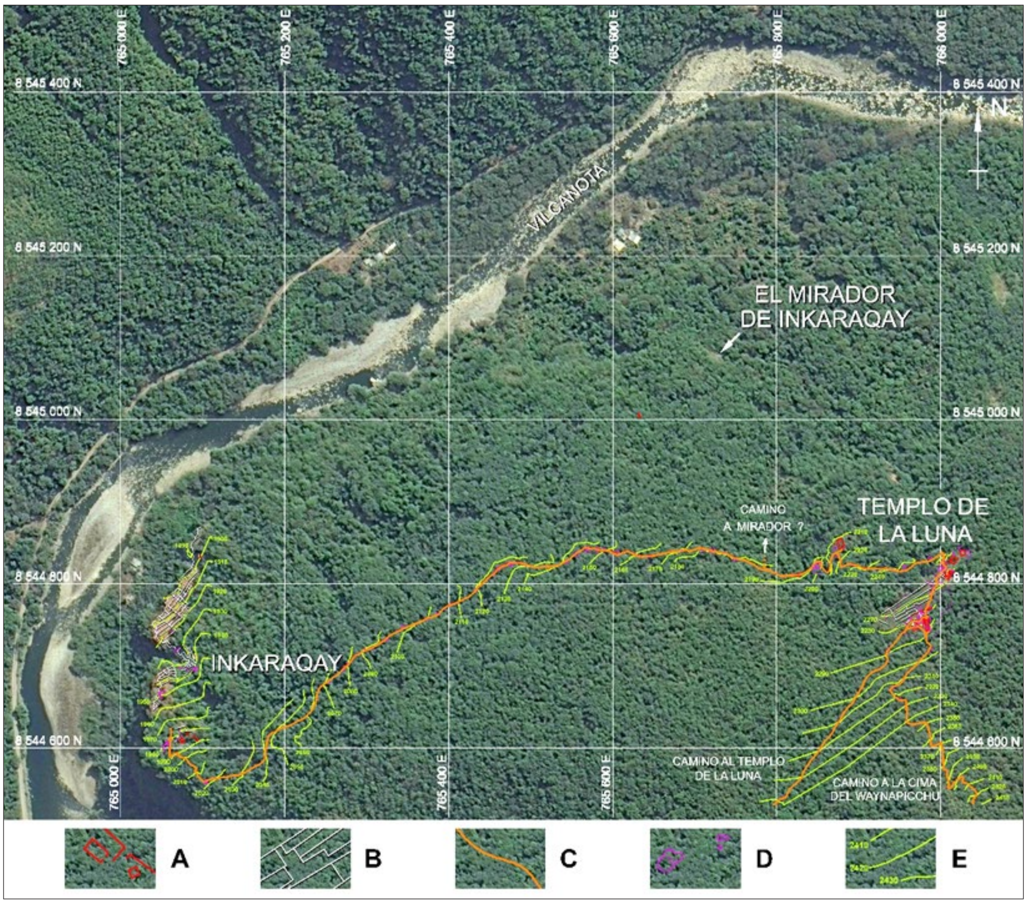

Fig. 5. Plan of the Inca road between Huayna Picchu and Inkaraqay; prepared by the Machupicchu National Archaeological Park's surveyors, courtesy DDC-Cusco, Google Earth image used for the background, edited and adjusted by J. Kościuk; A – Inca walls and buildings; B – terraces; C – Inca path; D – rock boulders; E – contour lines.
Ryc. 5. Plan drogi inkaskiej między Huayna Picchu i Inkaraqay; opracowany przez architektów i geodetów Parku Archeologicznego Machupicchu, dzięki uprzejmości DDC-Dusco, obraz z Google Earth użyty jako tło, edycja i dostosowanie J. Kościuk: A – inkaskie mury i budynki; B – tarasy, C – inkaska ścieżka; D – głazy kamienne; E – poziomice.

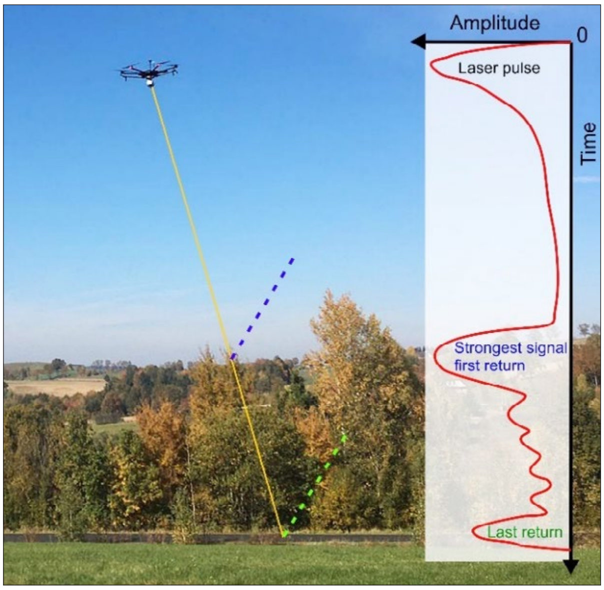

Fig. 6. Dual return single principle of Velodyne VLP-16 sensor; by B. Ćmielewski.
Ryc. 6. Zasada podwójnego pomiaru czujnika Velodyne VLP-16; oprac. B. Ćmielewski.

the Vilcanota River at an altitude of 2,012 masl. The site is located in very rugged terrain covered with dense rainforest. This area of the Park is outside any tourist routes and is visited only by the Park specialists for maintenance and monitoring works.

The former Director of the Park, Fernando Astete, discovered the El Mirador site in 1982, but the first limited-scale archaeological fieldwork was only carried out in 2012. Its essential result was recording the Inca road running from the Templo de la Luna (the last point on the tourist circuit) to the Inkaraqay archaeological site (Fig. 5). Some sites have also been surveyed and investigated along this road, but most of the area's architectural remains have been left unrecorded. This is mainly due to difficulty in the terrestrial prospection of such rugged and densely covered terrain.

Between 2013 and 2019, the Peruvian-Polish research team conducted more intensive work at El Mirador de Inkaraqay and proved that the site functioned as an astronomical observatory.[15] However, the relationship between El Mirador de Inkaraqay and the located to the west archaeological site of Inkaraqay remained unknown. The terrain between these sites is virtually unexplored. This situation motivated the authors of this study to use a UAV-mounted LiDAR to survey the area in search for possible vestiges of pre-Hispanic constructions concealed by the rainforest—an approach similar to that recently published research on Kuelap in the Peruvian Chachapoya department.[16]

Survey techniques

In the LiDAR survey, the topography of the terrain and the characteristics of the anthropogenic anomalies being searched for significantly impact the identification and interpretation process.[17] Also, processing this kind of data, particularly adjusting and adapting vegetation filtering algorithms, is challenging.[18] Filtering out vegetation cover, which results in a bare-ground 3D point cloud, is based on the LiDAR devices' feature to record several (at least two) returns from the probing signal (Fig. 6).

The resulting data quality greatly depends on the LiDAR system's ability to penetrate the vegetation cover. This, in turn, is influenced by the laser beam footprint size (as a resultant of LiDAR technical parameters and flight altitude) and the characteristic of the terrain surveyed—the density of the vegetation cover, the ground's reflectance and its directivity of the reflection. Since only some of the impulses reach the ground itself; it results in a significant reduction in the ground surface sampling density: typically, from only a few to a dozen or so reflections per square meter.

The principle that the sampling resolution should be at least twice the size of the anomaly being searched for results in significant requirements for the minimum sampling resolution useful in the given conditions. In cases where large objects are being detected (moats, barrows, or extensive embankments), even one to two points per square meter may be sufficient. The situation changes when one searches for the relics of buildings where wall relicts are only a few meters long and hardly broader than half a meter. Even a dozen or so of ground-points per square meter may turn out to be insufficient. Another aspect to consider is the cost and logistics of the LiDAR survey using airplanes or helicopters. It is profitable only for large-scale studies covering tens, if not hundreds of square kilometers, but unfeasible for studies spanning only a few square kilometers of the area remote from any airfields and LiDAR surveying companies. In such conditions, the UAV based LiDAR survey seems more rational.

UAV LiDAR system used in the study

With its lifting capacity of 9.6 kg, the octocopter assembled at LabScan3D from commercially available parts served as the platform for the entire system. The sensing system was equipped with a Velodyne VLP-16 laser scanner combined with a dual-frequency NovAtel OEM615 GNSS receiver with a survey-grade antenna and an Sensonor IMU STIM300. The technical specifications are summarized in Table 1.

All the sensors, together with an AAEON microcomputer for collecting and storing the data, were assembled in an aluminum box fixed by quick-release coupling plate (Fig. 7). The entire system (UAV and LiDAR) was powered by two six-cell Li-Ion batteries with a capacity of 12.5 Ah each, enabling the drone to fly at an altitude of ca. 2,500 masl for around 17 minutes, covering 200,000 to 250,000 m^2 of the terrain on average. Because the system had only one survey-grade GNSS antenna, a kinematic alignment was necessary

Fig. 7. The LiDAR system assembled at LabScan3D and used in the study; photo by J. Kościuk.
Ryc. 7. System LiDAR złożony w LabScan3D i wykorzystany w badaniu; fot. J. Kościuk.

to obtain the correct azimuth. Additional equipment included a ground station for differential trajectory processing with a dual-frequency NovAtel OEM615 GNSS receiver and a GNSS antenna. The total cost of all components did not exceed 20,000 US$, which is about a quarter of the cost of commercial off-the-shelf LiDAR systems intended for UAVs.

Four flights, all in the visual line of sight (VLOS) mode, were accomplished for each of the two sites. A critical factor was the sky's visibility, which was limited by the surrounding steep hills since the site is located at the bottom of the Vilcanota Valley. For this reason, a flight altitude for the Chachabamba site was set to 60 m above ground level, and an optimal time window for the survey was selected to ensure the largest number of satellites visible.

For the Inkaraqay site and the surrounding area, it was impossible to set up a trajectory line at one altitude. Steep slopes, limited choice of takeoff and landing sites, and varying height of the vegetation forced flight in manual mode following the site topography with 20–40 m separation from upper tree branches.

Data acquisition and processing

The data from sensors were collected in the internal memory of the attached microcomputer. The precise time pulse from the inertial measurement unit (IMU) with NMEA GPRMC header was fed into the scanner sensor allowing time stamps for each information packet. Parallelly, the raw data from the IMU and GNSS sensor were also stored in a binary file. Using sensor fusion in Extended Kalman Filter[19] implemented in Novatel Inertial Explorer commercial software, the precise trajectory was calculated from this data. The georeferencing of LiDAR 3D point cloud has a typical workflow that requires three sets of data: trajectory, laser scanner measurements, and calibration parameters (translation and rotation values between laser sensor and IMU unit).[20] Data acquisition and processing workflow are illustrated in Fig. 8.

This ensured the transformation of the local scanner coordinate system (s-frame) into the Earth-Centered/Earth-Fixed (ECEF) coordinate system (e-frame), and after that, transformation into an appropriate geodetic projection.[21] The scanner measures the range and angles in time (t), from which the Cartesian coordinates of s-frames are calculated. Before the transformation to ECEF, the scanner calibration parameters must be added. To obtain calibration parameters, we used the Iterative Closest Point (ICP) algorithm.[22]

Table 1. The technical specifications of the components

Laser sensor – Velodyne VLP-16	
number of diodes	16
horizontal field of view (as mounted on the drone)	30° (+15° to -15°)
measurement range	up to 100 m
measurement accuracy	± 0.03 m
number of returns	2
GNSS sensor Novatel OEM615	
horizontal GNSS/IMU accuracy	0.010 m
vertical GNSS/IMU accuracy	0.020 m
IMU sensor - Sensonor STIM300	
IMU attitude for roll and pitch	0.006°
IMU attitude for yaw	0.019°

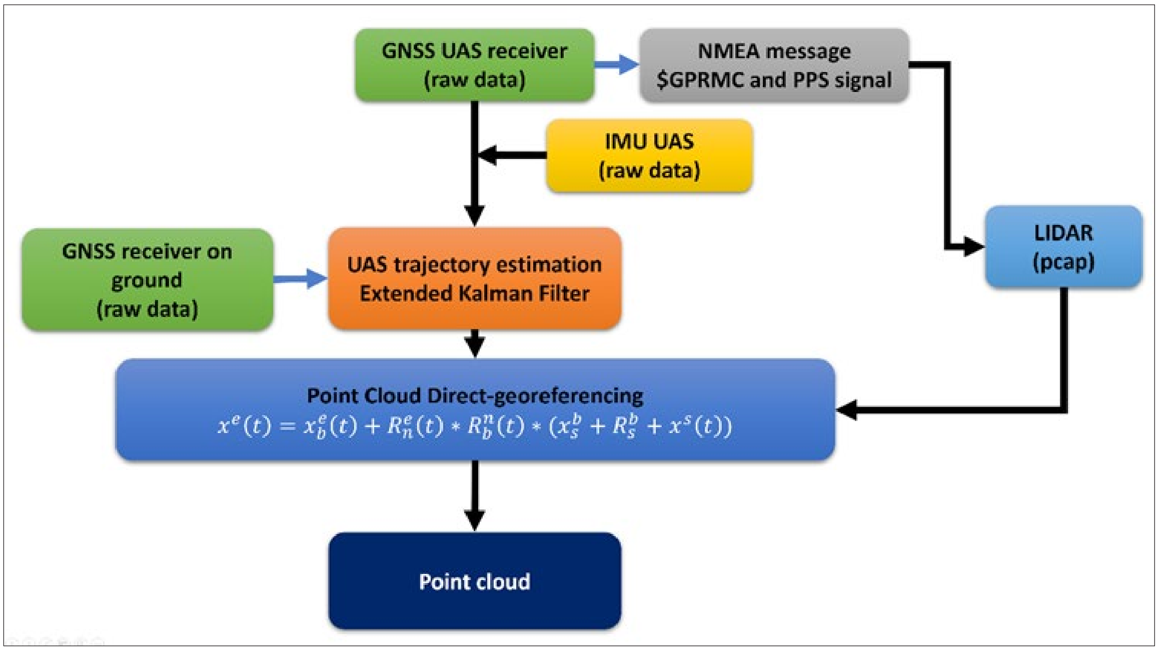

Fig. 8. Main steps of data acquisition and processing; by B. Ćmielewski.
Ryc. 8. Główne kroki pozyskiwania i przetwarzania danych; oprac. B. Ćmielewski.

The transformation from s-frame to e-frame involves several steps. The trajectory has to be calculated from collected GNSS and IMU data using a tightly-coupled EKF (Extended Kalman Filter) with a known offset between the IMU and GNSS antenna. This step was done in Novatel Inertial Explorer commercial software. The results of the trajectory reconstruction were IMU (b-frame origin) positions in e-frame $xb(t)$ and IMU attitudes (angles) in n-frame. These served as input data to calculate the rotation matrix $Rb(t)$. Next, the calculated coordinates of the points given in s-frame $x(t)$ were transformed into e-frame according to the following direct georeferencing equation [1].[23]

$$x^e(t) = x_b^e(t) + R_n^e(t) \times R_b^n(t) \times \left(x_s^b + R_s^b + x^s(t)\right) \quad [1]$$

where:

$x^s(t)$ – the Cartesian coordinates of a point in s-frame;
x_s^b – the position of the s-frame origin in the IMU coordinate system (b-frame);
$R_s^b = R_s^b(\omega, \varphi, \kappa)$ – the rotation matrix from s-frame to b-frame;
$R_b^n(t) = R_b^n(r(t), p(t), y(t))$ – the rotation matrix from b-frame to n-frame;
$R_n^e(t) = R_n^e((\lambda(t), \varphi(t))$ – the rotation matrix from the navigational topocentric coordinate system (n-frame) to e-frame;
$x_b^e(t)$ – the position of b-frame origin in e-frame;
$x^e(t)$ – the point coordinates in e-frame.

In the next phase of data fusion, the point cloud in the e-frame was transformed into a national coordinate

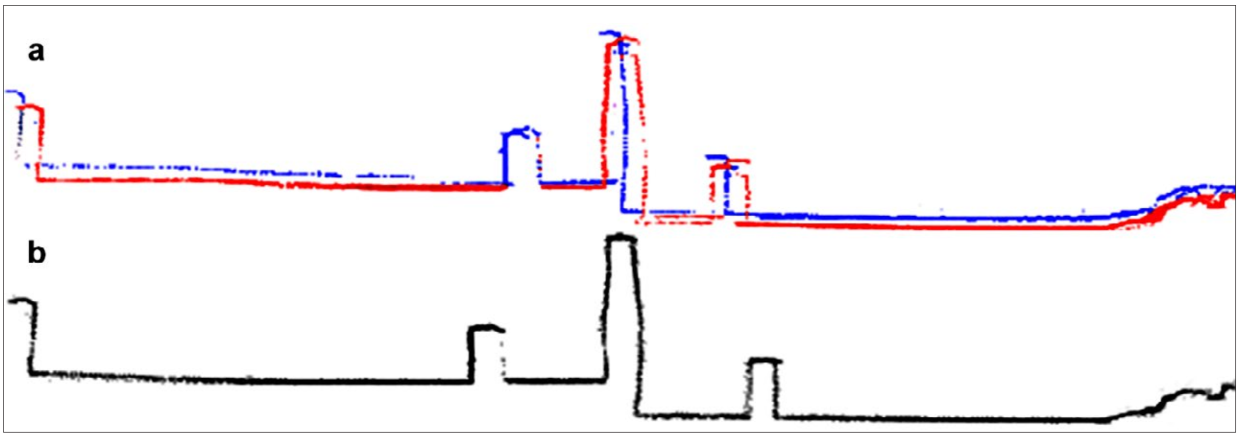

Fig. 9. Impact of calibration parameters on the computed cloud; by B. Ćmielewski; a – only rough calibration and offsets; b – rough and precise calibration parameters applied.
Ryc. 9. Wpływ kalibracji parametrów na obliczoną chmurę punktów: a – jedynie pobieżna kalibracja i offsetowanie; b – zastosowana pobieżna i dokładna kalibracja parametrów; oprac. B. Ćmielewski.

system by applying an appropriate projection (UTM 18S). The height was also converted from ellipsoidal to orthometric heights by applying the separation value between ellipsoid and geoid from the global geopotential model (EGM2008).

Since the entire procedure involved numerous steps, dedicated software was developed at LabScan3D facilitating all data processing and making the entire process more user-friendly. Firstly, the dataset with measured calibration parameters was processed—offsets and rough rotation between IMU and laser scanner. Later, after using the ICP algorithm, the precise calibration was added. This significantly improved the results (Fig. 9). The final product was a 3D point cloud in *.las format.

The accuracy of the obtained 3D point cloud (differences in a mismatch from estimated maximal error) was less than 8 cm. The resulting file constituted the input data for the last step of processing involving noise filtering and classification. The Velodyne VLP-16 sensor records separate returns only when the distance between the two objects reflecting laser pulses is one meter or more.[24] This means that some of the recorded 3D points might be lacking correct spatial information. Such the noise points were filtered out using TerraScan software. The same software was used to classify the 3D point cloud—filtering out all the vegetation cover and leaving only the bare-ground 3D points. The so-called "ground routine," which builds a surface model from the initial ground points, has been used.[25] Since in rainforest conditions, most wall relics are covered with a dense layer of lianas and lichens, an additional class to the filtration process has been introduced—"the ground class + 0.5 m." To assess our LiDAR system's effectiveness, the resulting data density was compared with chosen data from a helicopter flights equipped with a long-range LiDARs (Table 2).

Data post-processing and visualization

Visualization techniques for digital elevation models (DEM) are often used to analyze and interpret archaeological relics hidden under a vegetation canopy.[28] Therefore, the *.las data classified and stripped of vegetation were imported into the ArcGIS 10.5 software package to create a GeoTIFF DEM file. A standalone tool, Relief Visualisation Toolbox v.2.1 (RVT), further processed the DEM files.[29] Besides the generic hillshade method, four other visualizations modes also proved to help highlight and emphasize hidden relics:
— ultidirectional hillshade,
— local relief modelling,
— openness (positive and/or negative),
— sky-view factor.

Depending on the features of particular relics it was found useful to apply different visualization methods (Fig. 10). The preliminary results were analyzed by a team of archaeologists and data acquisition specialists, who determined which particular anomaly could be associated with anthropogenic traces in the surveyed sectors.

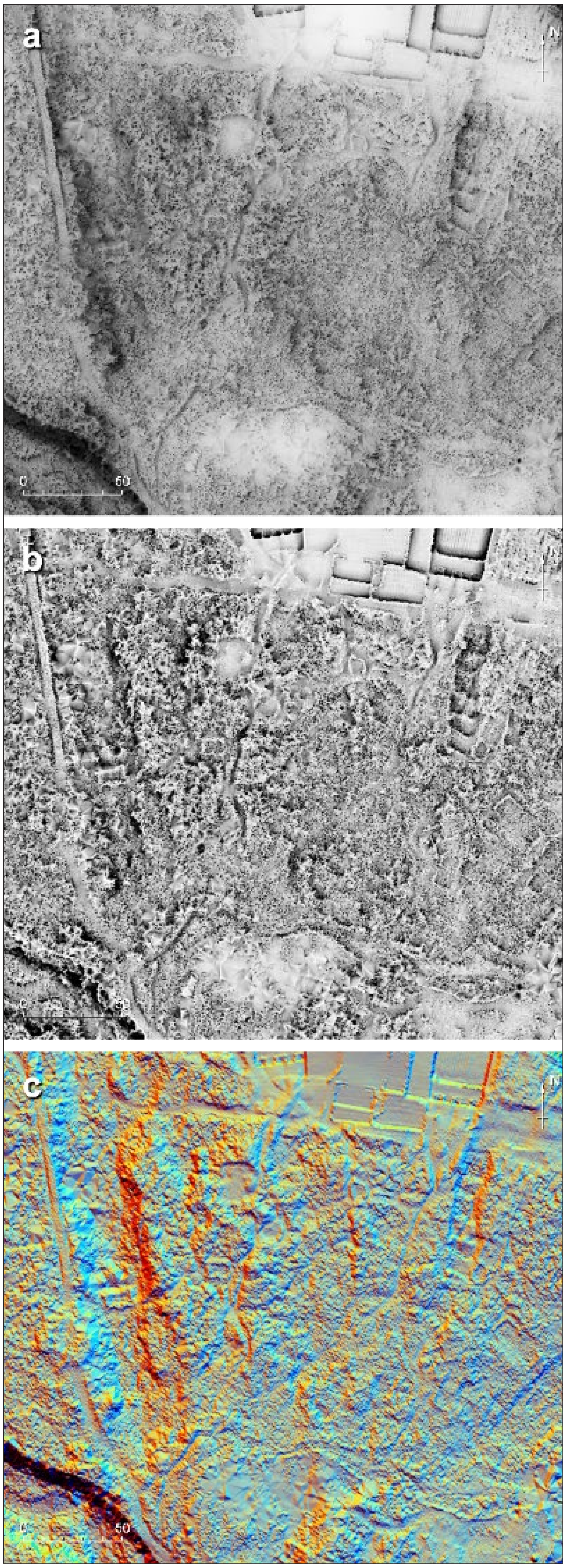

Fig. 10. Comparison of different visualization methods – the Chachabamba archaeological site example; a – sky-view factor; b – openness positive; c – multidirectional hill shading; by B. Ćmielewski.

Ryc. 10. Porównanie różnych metod wizualizacji – przykład stanowiska archeologicznego Chachabamba: a – współczynnik widoku nieba; b – pozytyw otwartości; c – wielokierunkowe cieniowanie wzgórz; oprac. B. Ćmielewski.

Table 2 Comparison of LiDAR datasets return signals

Data	Average 3D point cloud density		
	all returns [pts/m²]	ground class only [pts/m²]	ground class + 0.5 m [pts/m²]
Inkaraqay (LiDAR UAV)	ca. 513	10.6	25.3
Chachabamba (LiDAR UAV)	ca. 219	13.2	72.2
Sample data received from Machu Picchu National Archaeological Park authorities* (long range LiDAR on a helicopter)	-	1.3÷1.4	-
Uxbenká (Belize) (long range LiDAR on the crew-maned platform)[26]	20.1	2.7	-
Typical LiDAR datasets ground return signals in the Maya regions of Belize (LiDAR on the crew-maned platform)[27]	-	1.1÷5.3	-

** Courtesy of DDC-Cusco.*

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Abstract

Besides the well-recognized central part, the National Archaeological Park of Machupicchu encompasses approximately 60 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 aeroplanes 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 discuss methods of data accumulation, filtration, classification and different visualization algorithms pointing to challenges related to UAV LiDAR use. The second part of this article will present the preliminary results for the LiDAR survey over Chachabamba and Inkaraqay sites and the first validation of the results.

Streszczenie

Obok dobrze zbadanej centralnej części, Narodowy Park Archeologiczny Machupicchu obejmuje także ponad 60 mniej znanych stanowisk. Przykładami są tutaj Chachabamba i Inkaraqay. Na stromych, porośniętych gęstym lasem deszczowym zboczach tradycyjne metody prospekcji terenowej nie gwarantują wykrycia wszystkich struktur o antropogenicznym charakterze, natomiast pomocne mogą być pomiary LiDAR (*light detection and ranging*) z pokładu samolotu lub helikoptera. Autorzy proponują alternatywną metodę z użyciem zamontowanego na dronie LiDAR-a, zdolnego do wykrywania reliktów murów o wysokości poniżej jednego metra. Główne zalety tej metody to łatwość i prędkość prospekcji, wysoka gęstość chmur punktów 3D oraz zdolność do penetracji pokrywy leśnej. Przedstawiono metodę zbierania danych, filtracji i klasyfikacji oraz algorytmy wizualizacji wyników. Jednocześnie wskazano wyzwania związane z użyciem systemów UAV LiDAR. Druga część artykułu zaprezentuje pierwsze wyniki pomiarów lidarowych w Chachabamba i Inkaraqay oraz ich wstępną ich ocenę.