Capturing Complexity

Toward an Integrated Low-Altitude Photogrammetry and Mobile Geographic Information System Archaeological Registry System

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Archaeologists have been aptly called "the prisoners of space" (Goldstein 2000). Archaeological inference, analysis, and interpretation rely fundamentally on spatial data: location, orientation, style, and other attributes of objects and features in space. But methods of spatial registry have developed unevenly over different scales. At the small end of the spectrum, archaeologists have developed virtually unique and unmatched cartographic techniques for documenting micro-scale phenomena (for instance, at the level of features in an excavation context).[1] At the other end of the spectrum—at subregional to interregional scales—archaeologists

ABSTRACT

Medium-scale archaeological phenomena (large settlements, landscape features and infrastructural systems, road networks, etc.) pose significant challenges to archaeological documentation. Traditionally, such features are mapped either schematically or via labor-intensive (or otherwise costly) high-resolution methods. The advent of inexpensive, packable unmanned aerial vehicles (UAVs) and lighter-than-air platforms, combined with increasingly sophisticated photogrammetric and mobile geographic information system (GIS) software systems, presents opportunities for improving on these compromises. Here, we present results from test flights and photogrammetric mapping using UAVs and a meteorological balloon, combined with mobile GIS-based attribute registry of architectonic features at a large, complex colonial planned settlement (Mawchu Llacta de Tuti) in highland colonial Peru. First, the operating parameters of UAVs are presented, as well as the imagery capture and photogrammetric processing work flows. Second, we provide an overview of the tablet-based mobile GIS system used to digitize a site plan (based on the imagery from the UAV) and register architectural attributes from each building. The results from initial testing suggest that in the near future, such combined close-range photogrammetry and mobile GIS-based systems will significantly enhance and expedite high-resolution data registry of a wide range of archaeological features, sites, and landscapes.

Fenómenos arqueológicos de escala media (asentamientos grandes, rasgos de paisaje y sistemas de infraestructura, redes de caminos, etc.) presentan retos significativos para la documentación arqueológica. Tradicionalmente se levantan planos de tales rasgos o esquemáticamente o por métodos de alta resolución necesitando labor intensivo (o costosos en otros sentidos). El advento de vehículos aéreos no tripulados ("drones" o UAV) económicos y portátiles, tanto como plataformas más leves del aire, combinado con sistemas de información geográfica y software fotogramétrico cada vez más sofisticado presenta oportunidades para mejorar estos compromisos. Aquí presentamos los resultados de los vuelos iniciales de prueba y ortomapeo tridimensional usando UAV y un globo meteorológico, en combinación con un Sistema de Información Geográficas (SIG) móvil para el registro de atributos de rasgos arquitectónicas en una grande y complejo asentamiento planificado colonial (Mawchu Llacta de Tuti) en la sierra suroeste del Perú. En primer lugar, se presentan los parámetros de funcionamiento de los UAV, así como la captura de imágenes y los flujos de trabajo de procesamiento fotogramétrico. En segundo lugar, ofrecemos una visión general del sistema SIG móvil utilizada para digitalizar un plano del sitio (basado en los imágenes procesados del UAV) y para registrar los atributos arquitectónicos de cada edificio y rasgos visible en la superficie del sitio. Los resultados de las pruebas iniciales sugieren que en un futuro próximo, tales sistemas combinados entre SIG móvil y fotogrametría de baja altitud mejorarán de manera significativa y acelerará el registro de datos de alta resolución de una amplia gama de sitios arqueológicos y las características del paisaje.

have developed increasingly sophisticated survey methods over the past half century. A vast range of archaeological phenomena between these two scales, however, are still typically mapped only schematically or through costly or labor-intensive methods. The conventional symbols for the pyramidal temples of Maya cities and the platform mounds of Mississippian centers, or the schematic representations of agricultural terracing and irrigation systems (canal inlets, valves, etc.), come to mind as examples. The analytical poverty of such schematics is especially apparent in contrast to how much data archaeologists tend to wring out of small, analytically important features, such as posthole molds, stains, and textural changes in house floors, let alone the richness of pottery or other artifact classes.

In short, as scale increases, the complexity of the phenomena of interest almost invariably increases as well, but cartographic representations of them (by necessity) generally have not. Capturing the complexity of mid-scale archaeological phenomena has been just beyond the budgetary, computational, and methodological capacities of most research projects. The recent proliferation of unmanned aerial vehicles (UAVs, popularly known as "drones") and other low-altitude platforms equipped with digital cameras, combined with increasingly sophisticated photogrammetric software, increasing computational power, and mobile geographic information systems (GIS), now puts accurate and high-resolution representation of mid-scale phenomena within reach of even relatively small research projects. Here, we outline an approach for low-altitude aerial imagery capture using UAVs and lighter-than-air platforms, photogrammetric processing, and feature registry via GIS. Beyond generating high-resolution air photos or 3-D models, our focus is on developing an integrated system that is efficient, robust, and analytically rich for mid-scale archaeological phenomena. We outline our approach to mapping a large, architecturally complex settlement in a challenging environmental setting: a planned colonial town built in the location of a former Inka center in the high-altitude reaches of the Colca Valley of southern highland Peru. In outline, the system we developed involves the following steps:

(1) Imagery capture via fixed-wing UAVs and meteorological balloons using digital cameras.

(2) Processing of imagery into orthomosaics, point clouds, digital elevation models (DEMs), textured 3-D meshes, and other products using commercial photogrammetric software (Agisoft PhotoScan Pro).

(3) Architectural survey via tablet-based mobile GIS, using the orthomosaics as base imagery. During the survey, features are digitized as vector themes on screen, and attribute forms are completed for each feature.

(4) Integration of the above data in a master GIS.

This approach came about as a solution to the specific problems of a long-term research project, but it is widely applicable and more easily implemented in many other environmental contexts. The discussion is pragmatic rather than highly technical in nature; we describe budgetary aspects, summarize each step in the cartographic registry process, identify work flow bottlenecks and problematic aspects, and suggest solutions and improvements. Though the technical hurdles to adopting such a system are not trivial, the benefits are considerable and extend beyond academically oriented archaeology. Low-altitude aerial photogrammetry enables the rapid and cost-effective production of a 3-D repository of archaeological sites, features, and contexts. Such repositories are of obvious research value and can also act as a virtual archive for cultural heritage management (see, e.g., Ioannides et al. 2012). Similar techniques are readily adaptable to smaller, excavation-scale contexts via handheld and pole-based close-range photogrammetry. We envision a not-distant future in which a suite of such techniques is de rigueur in archaeological practice.

EXPLODING FIELDS: UAVS, PHOTOGRAMMETRY, MOBILE GIS

The technologies underlying UAVs, photogrammetry, and GIS are developing rapidly and becoming more affordable. News stories of the potential research and commercial applications of UAVs are ubiquitous in popular media. In just the past few years, the UAV sector has expanded from a small hobbyist community and a few specialized manufacturers using proprietary systems to a diverse array of do-it-yourself (DIY) and commercial offerings.

Advances in open-source UAV technology have made possible the assembly of autonomous air vehicles entirely from off-the-shelf components and open-source software. Any UAV typically requires the following components to achieve functional autonomous flight: an airframe and its associated components (e.g., batteries, propellers, and motors), onboard sensors for telemetry (e.g., GPS, altimeter, and compass), an autopilot to act upon telemetry data, and software for autonomous UAV control (Everaerts 2008). Radio-controlled hobby aircraft suppliers provide a low-cost means of acquiring the necessary components to produce a functional aircraft. Companies in the hobby UAV industry, such as 3D Robotics, offer autopilot and telemetry packages (Popper 2013). UAV operators can easily and rapidly develop flight plans and analyze collected flight data using free and open-source software such as the Ardupilot Mission Planner (Ardupilot-Mega 2013).

Modern image-collection techniques for archaeological site survey include the use of camera-equipped balloons (Bitelli et al. 2004), radio-controlled helicopters (Theodoridou et al. 2000), kites (Aber et al. 1999), and other fixed-wing and rotor-based aerial vehicles (Chiabrando et al. 2011; Eisenbess et al. 2005; Mozas-Calvache et al. 2012; Remondino et al. 2011; Verhoeven 2009). This overhead imagery is usually combined with georeferenced ground control points (GCPs) and/or terrestrial survey or laser scans (Lambers et al. 2007). The imagery is mosaicked using photogrammetric software to create a single orthomosaic of the area of interest. The photogrammetric software also uses structure from motion (SfM)-based techniques to reconstruct stereoscopy and, thus, 3-D representations of the area of interest via point clouds, textured wire-frame models, and DEMs.

Other alternatives to photogrammetry, such as ground-based light detection and ranging (LiDAR) techniques, can be cost prohibitive, often do not provide coregistered visible-light orthoimagery (Wiechert and Gruber 2009), require extensive postprocessing, and can be more difficult to use in terms of placement and configuration than UAV-based approaches (Barsanti et al. 2012; Eisenbess et al. 2005). Aerial LiDAR data collection is of proven and even transformative value to understanding archaeological landscapes (especially in heavily wooded areas [see Chase et al. 2012; see also Chase and colleagues' article in this volume]), but it is costly. UAVs equipped with LiDAR systems, while feasible, can be expensive and heavy, resulting in minimal flight times when compared with camera-equipped alternatives (Lin et al. 2011). Smaller and lighter LiDAR and laser range finders are likely to emerge in the near future. Pilot projects with compact LiDAR (Glennie et al. 2013), spectral sensors beyond visible light (Brumana et al. 2013; Casana et al. 2014), and multisensoral systems (Jaakkola et al. 2010) have produced promising results.

The theoretical underpinnings of generating mosaics from overhead imagery have been discussed (Chiabrando and Spanò 2009), and recent developments in commercial and open-source photogrammetric software have led to user-friendly products that make mosaicking techniques available to those who may be unskilled in the underlying theory. These SfM-based products include commercial photogrammetric software, such as Agisoft's (2014) PhotoScan, which allows for the straightforward creation of orthomaps, DEMs, and point clouds based solely on a set of images and GCPs as input. A sizable literature on the use of PhotoScan for aerial 3-D mapping in archaeology is developing (e.g., Chiabrando et al. 2011; Remondino et al. 2011; Verhoeven 2009; Verhoeven et al. 2012). VisualSfM (Wu 2013), an open-source offering, provides many of the same capabilities as PhotoScan. SfM has been used to document the state of archaeological sites that risk damage from looting and industrial expansion, as well as livestock and human traffic (Hesse 2013).

Lightweight, human-packable UAVs are becoming increasingly prevalent and have been used in some capacity for archaeological surveying tasks (Haubek and Prinz 2013). These UAVs are typically fixed-wing or rotor-based in design and may include both commercially available vehicles and those designed by experimenters (Bendea et al. 2007; Eisenbess et al. 2005; Fallavollita et al. 2013).

Helicopters and multirotor aircraft (e.g., quadrotors, hexrotors) are a popular choice for photogrammetric tasks due to their ability to take off and land in compact spaces, increased maneuverability compared with fixed-wing vehicles, ease of deployment, and hovering capabilities (Sauerbier and Eisenbess 2010). Rotor-based air vehicles can suffer from certain drawbacks, such as limited payload capacity (a problem exacerbated at high altitudes due to decreased air density), low battery life compared with that of similarly sized and powered fixed-wing aircraft, and instability in high wind and other adverse weather conditions (Eisenbess 2009). In high-altitude, high-relief areas (such as glacial moraines) where takeoff and landing of a fixed-wing aircraft may not be feasible, rotor-based UAVs can be a good choice. Multirotor craft have been flown reliably with multispectral sensors as high as 5,200 m asl. The additional thrust required to achieve lift at such elevations necessitates larger propellers, frame dimensions, and batteries (and thus more weight), which limits flight time to approximately 10 to 15 minutes (Oliver Wigmore, personal communication 2014).

Systems have also become much more affordable. DIY UAV systems made from off-the-shelf components are now within the budgetary constraints of even relatively small-scale projects (e.g., dissertations). A large and active online DIY community facilitates entry into the technology through detailed build lists and videos and discussion forums for consulting expert hobbyists and professionals (e.g., DIYdrones.com 2014; Flightriot.com 2014). With these trends, the field of UAV-based photogrammetry in archaeology is at an inflection point: though it is still the domain of early adopters, the technology, costs, and technical methods required are now accessible to a much broader user base.

That said, off-the-shelf fully autonomous UAV flight is not a realistic expectation now or in the near future. Considerable pilot training is required even if only for initial test and calibration flights. Crashes will occur, and considerable technical knowledge is required to maintain UAVs and adjust their flight parameters (via changes to hardware and software controls). As we discuss below, small, packable UAVs also come up against physical constraints of air density in warm, high-altitude areas. For many projects (especially those with limited budgets and technical personnel), tethered lighter-than-air platforms—helium balloons or simple blimps outfitted with digital cameras—are probably a better option as a simpler, less expensive, and more reliable aerial imagery system. Our experiences with UAVs and balloon-based systems are discussed below.

RESEARCH CONTEXT: A PLANNED COLONIAL TOWN IN THE HIGH PERUVIAN ANDES

This project developed a means of mapping the site of Mawchu Llacta, a large and architecturally complex settlement in the southern highlands of Peru with occupations from the Late Horizon (1450-1532 C.E.), the Spanish Colonial period (1532-1821 C.E.), and the subsequent republican era until its abandonment in 1843 (Figure 1). Mawchu Llacta is a planned colonial town (referred to as a *reducción*—literally "reduction town") built over a major Inka-era center in the *puna* (high-elevation grasslands) at an elevation of 4,060-4,125 m asl (Figure 2). The town was founded as part of the *reducción general de indios* (general resettlement of Indians)-a massive forced resettlement program instituted in the course of just a single decade—the 1570s. Some 1.5 million native Andeans were forcibly resettled

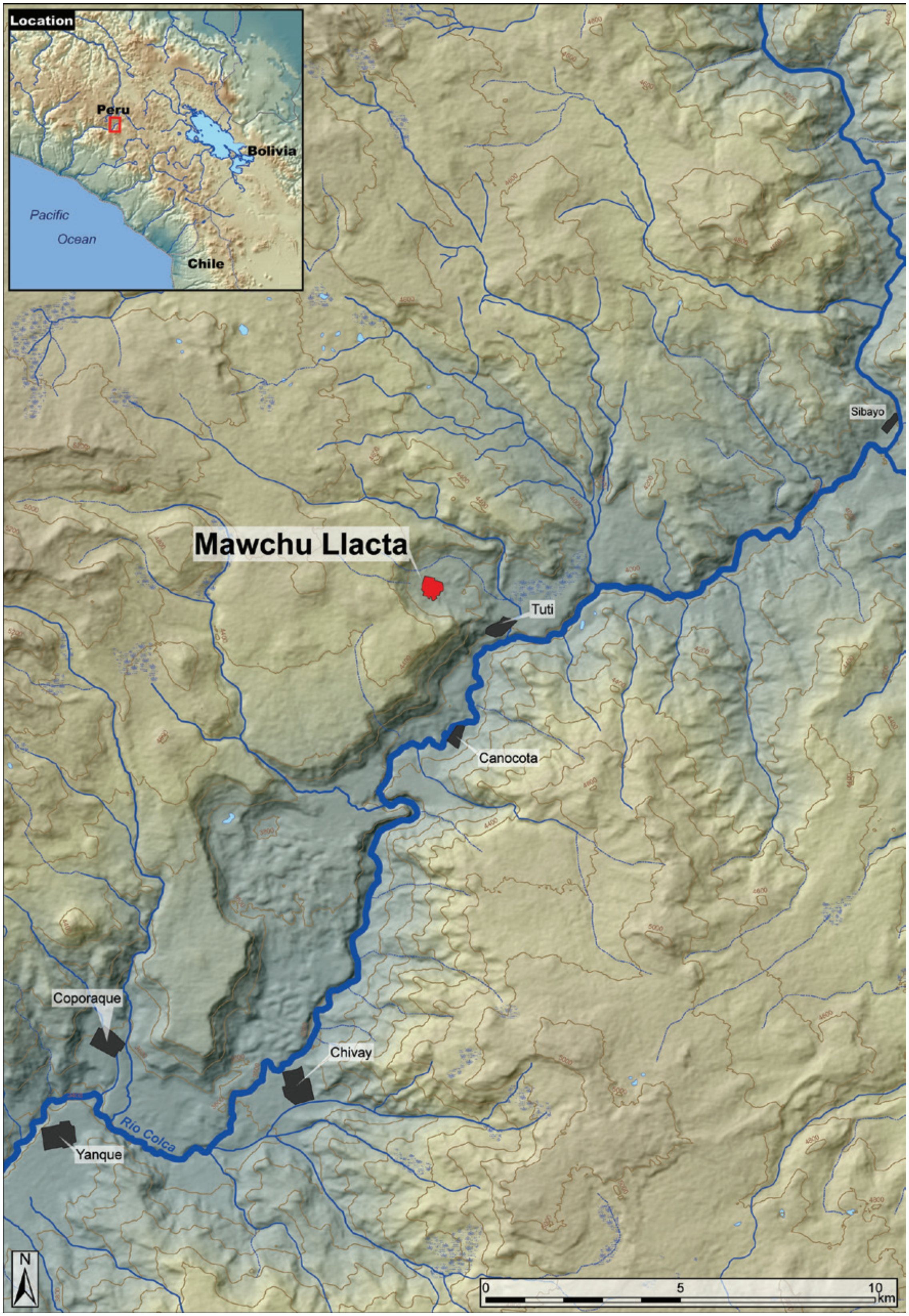

FIGURE 1. Location of Mawchu Llacta (red) and contemporary towns (gray).

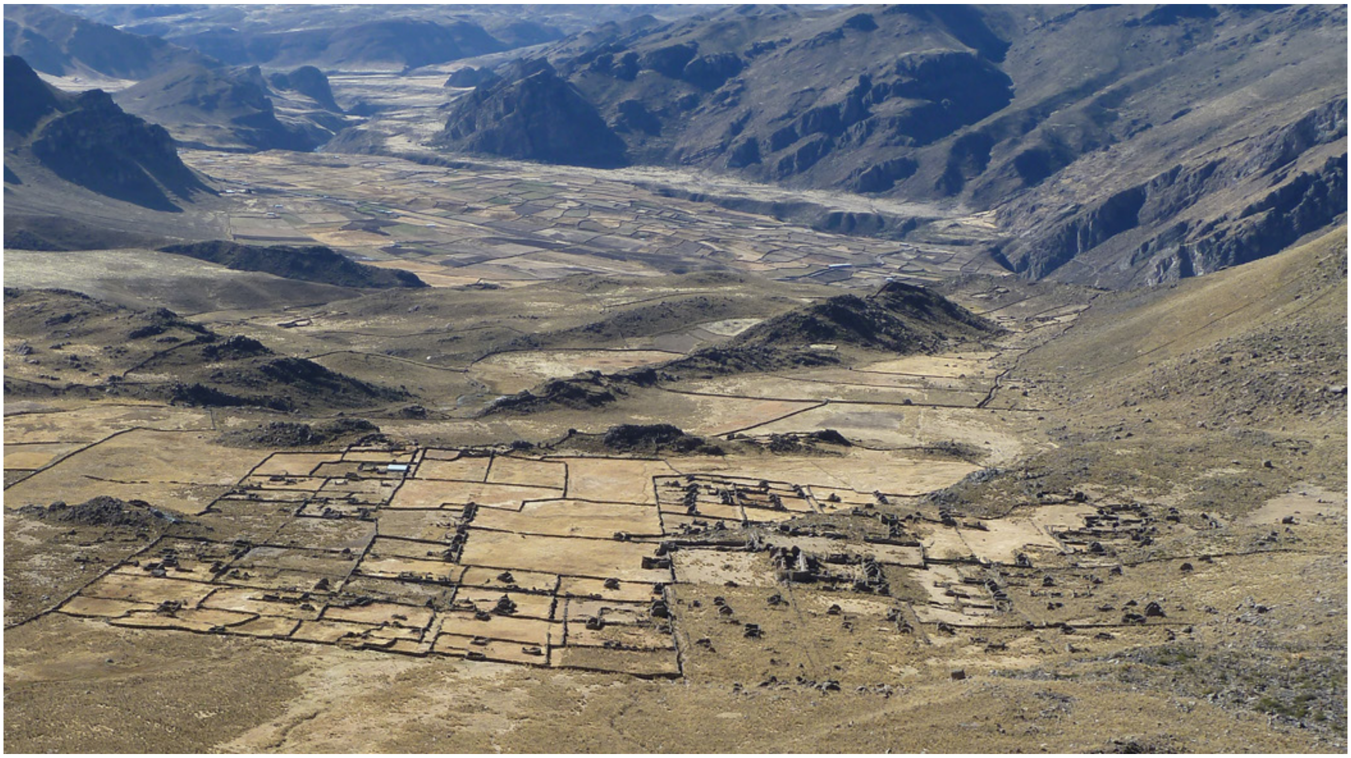

FIGURE 2. Panorama of Mawchu Llacta from the west.

into more than a thousand such *reducciones* built on gridded street plans with central plazas and churches. This program was the centerpiece of an overarching plan by Viceroy Francisco de Toledo to establish a new colonial social order in Peru, following three decades of plunder, indigenous revolt, and Spanish factional wars. Beyond a reflection of an envisioned social order, *reducción* was intended to generate "civilized," Christian subjects and ultimately inculcate the workings of a new colonial society.

Despite the scale and importance of the general resettlement of Indians, fundamental questions regarding its local implementation and effects remain unaddressed because the program left very little local-level documentation, and the archaeology of *reducciones* remains in its infancy. Since the built environment was the central medium through which such transformations were to occur, detailed architectural plans are of primary analytical importance. The excellent architectural preservation at Mawchu Llacta provides an ideal context for such research, but the complexity and extent of the architectural remains also pose significant mapping challenges. Most of its fieldstone buildings are more than 50 percent preserved, and many remain nearly intact (see Figure 2). The settlement was occupied through the mid-nineteenth century (it was abandoned as its residents relocated in 1843 to the modern town of Tuti). This long occupational sequence presents both opportunities to analyze diachronic processes through the colonial and early republican eras and interpretive challenges because of complex horizontal stratigraphic relationships among architectural elements. Detailed mapping is required to clarify these relationships. With more than 500 estimated buildings and many hundreds of other walls delineating blocks, domestic compounds, and other unroofed areas, it was clear while planning the project that detailed mapping with traditional methods (e.g., via differential GPS [DGPS] or total station) would require several field seasons. Low-altitude aerial photogrammetry combined with mobile GIS was chosen as a cost-effective and efficient methodology for overcoming these challenges.

Mawchu Llacta, however, poses significant environmental challenges to UAV performance and stability. Most fundamentally, at 4,100 m asl air pressure is dramatically lower than is typical at sea level (approximately 60 kPa, compared with 100 kPa at sea level). During the dry season of June to September, diurnal temperature differentials at Mawchu Llacta are quite large, with average low and high temperatures measuring 7°C and 22°C, respectively. "Hot and high" conditions, in which especially low air density results from high elevation and high ambient temperature, frequently occur from late morning through early afternoon hours. Mawchu Llacta is also only accessible by hiking 4 km with 400 m of vertical gain over steep and rocky terrain from the modern town of Tuti. There is no secure storage on-site. These factors place size limits on the UAV, since it would need to be packable.

Though multirotor designs are popular for their hovering capabilities, the scale of the site and its environmental conditions make human-packable rotor-based aircraft a suboptimal option. Various rotor-based designs, such as quad-, hex-, and octorotors, were simulated using the online flight dynamics calculation tool eCalc (Müller 2013). eCalc is a general engine calculation tool; therefore, the aerodynamics of a particular aircraft are not taken into account. Other, more robust, flight dynamics simulation tools exist, such as the open-source program AVL

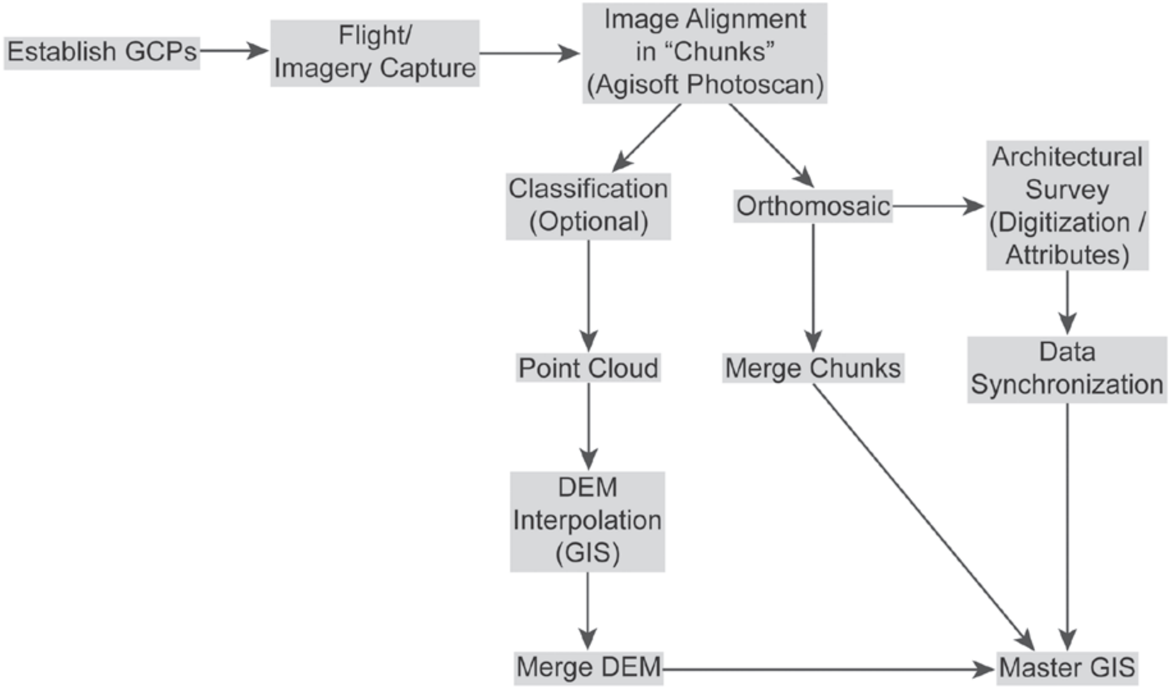

FIGURE 3. Project work flow.

(Drela and Youngren 2012); however, models of human-packable UAVs are generally not provided by simulation tools, and the time allowed for simulation did not permit the development of a model from scratch. eCalc calculations determined that, for the flight time and lift required, rotor-based designs were not practical. Due to the weight of the design itself, its intended payload, and the air density, flights by human-packable rotor-based designs would be very short in duration. Simulated flight times averaged eight minutes. Since Mawchu Llacta is a large and remote site with no nearby power sources, multiple battery changes would be required; returning to town to recharge batteries in between flights is impractical over a single workday. The challenges posed by Mawchu Llacta thus resulted in the deployment of fixed-wing UAVs.

THE WORK FLOW

In outline, the project work flow starts by establishing GCPs via total station or DGPS. Next, UAV or balloon overflight captures overlapping images at regular intervals while moving over the area of interest. The images are then processed by the Agisoft PhotoScan photogrammetric software for orthomosaic and 3-D model production. The resulting data products are then used as base imagery for digitization and architectural survey via mobile GIS or as terrain models and base orthoimagery for the project master GIS. Features are manually digitized as vector themes (points, lines, polygons) on-screen in the mobile GIS, and attributes are recorded for each feature. Data are then synchronized to a master GIS. This work flow is outlined in Figure 3. Below each step is described in further detail.

ESTABLISHING GROUND CONTROL POINTS

Prior to overflight, ground control points are required to reference the imagery to a common coordinate system for the project. The GCPs should be interspersed at semiregular intervals over the entire study area to be documented. There is no simple recipe for an optimal density of GCPs, as it is a scale-dependent process. In a given "chunk" (group of overlapping photos to be processed as a group in the photogrammetric software), 10-15 widely distributed (on both horizontal axes and the vertical axis) GCPs is recommended, but georectification (with diminished accuracy) can be achieved with as few as three GCPs. In our case, we eventually opted for a GCP spacing of approximately 40 m, coinciding with the intersections of the street grid of Mawchu Llacta.[2] The GCPs need to be shot with markers that are readily visible in the overhead imagery. We used 30-cm red plastic plates nailed into the ground with 20-cm nails, though the corners of buildings or walls would also work.[3]

Establishing GCPs is the most time-consuming field operation in the aerial photo documentation process. Our GCPs were shot with a total station and tied back to a master site datum, which was established via postprocessed DGPS, with submeter accuracy. With ~40-m spacing over the extensive area of the site, we recorded 138 GCPs (Figure 4). Subdecimeter DGPS or robotic total station registry can significantly reduce the time required to record GCPs.

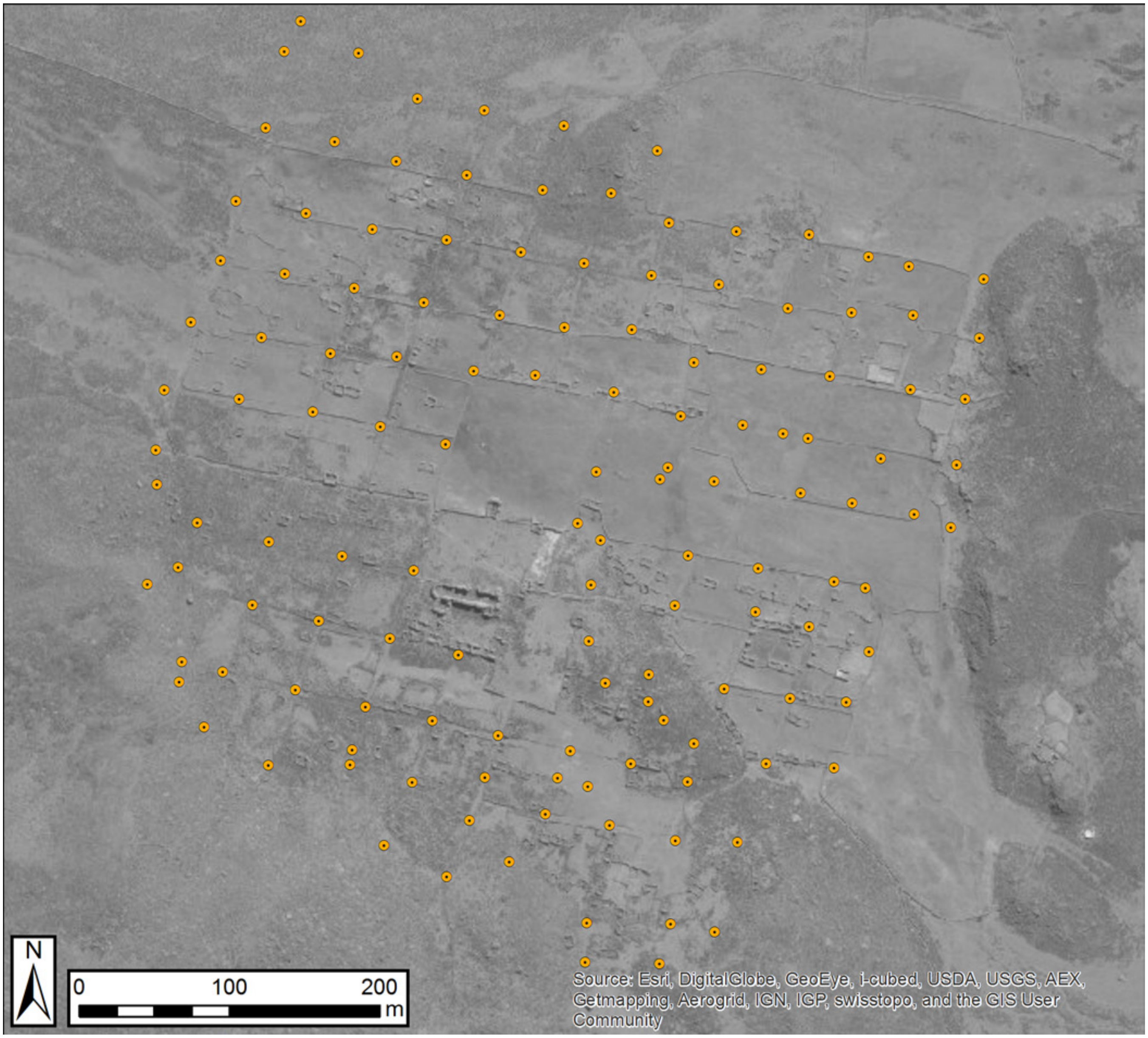

FIGURE 4. Ground control points for the 2013 field season.

OVERFLIGHT WITH UAV AND LIGHTER-THAN-AIR PLATFORMS

Compared with GCP registry, aerial imagery capture via UAV or balloon overflight is fast. A fixed-wing UAV flying at cruising speed (30-40 kn) in a lawnmower pattern (boustrophedon) and shooting photos every half second at an altitude of 30-50 m above the ground can document a 25-ha area in about 10 minutes. Crews walking a tethered meteorological balloon can cover a similar area in three to five workdays (depending on terrain, obstacles, etc.). With sufficient image overlap (~60 percent), features are documented from multiple angles to produce planimetrically correct composite orthophotos—that is, a nadir view of each feature without perspective distortion, rather than an oblique view, as is the case with features outside the center of the frame in a single aerial photo or satellite image.

The extreme elevation conditions of Mawchu Llacta, however, complicated UAV flight, as discussed below. Ultimately we achieved the best photogrammetric results using a tethered meteorological balloon.

Test Flights with the Aurora Flight Sciences Skate UAV (2012)

When we began work on this project during the spring of 2010, there were relatively few options available for fixed-wing UAV designs. We opted for the Aurora Flight Sciences Skate UAV

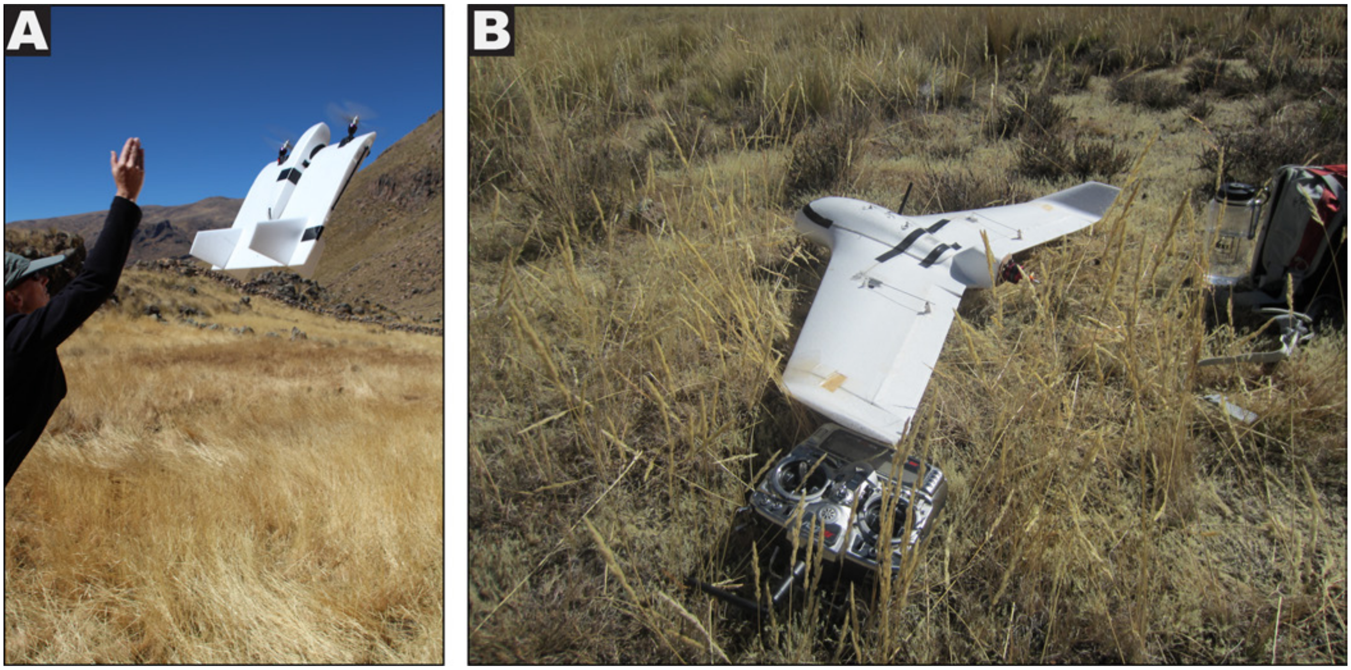

FIGURE 5. (a) Launching the Aurora Flight Sciences Skate unmanned aerial vehicle, 2012. (b) Skywalker do-it-yourself unmanned aerial vehicle (shown here without propeller), 2013.

(Figure 5), a small and packable fixed-wing UAV with a swappable camera/sensor pod and servo-controlled motors, which allows transition between vertical takeoff and horizontal flight, as well as the ability to loiter over an area of interest. It is a relatively costly system: two airframes plus the required base station (radio transmitter/telemetry, mission planner, etc.) totaled approximately $40,000.

At the time, the Skate was one of the few UAVs rated to fly at the elevation of Mawchu Llacta, but it had not been actually field-tested above 4,000 m. Aurora Flight Sciences sent an engineer with extensive flight experience to Peru to adjust the flight parameters of the UAV as needed and gather data on its flight characteristics at high elevation. The effects of elevation (low air density) and possibly hot and high conditions made flight a challenge. Flight was erratic, with frequent "porpoising." The vehicle crashed numerous times during full manual operation, requiring extensive repairs and replacements. Numerous experiments with different motor and propeller configurations and other flight control parameters enabled only limited manual flight. Efforts were focused on maintaining stable flight, rather than systematically collecting aerial imagery. Despite these challenges, the UAV gathered approximately 3,500 aerial images of the site in three flights.

DIY UAV (2013)

Given the difficulties of the 2012 season and rapid advances in DIY UAV technologies, we opted to build our own UAV from off-the-shelf parts for the 2013 field season. The eCalc simulator was used to evaluate the fixed-wing UAV alternatives.

The parameter selection began by choosing a suitable airframe. The Skywalker X-5 flying-wing airframe (Figure 5) was selected because it was human-packable and provided a large amount of interior space to house the necessary electronic components. The hobby aircraft community has generated configuration files that allow autonomous flight using the open-source Ardupilot autopilot system (Castro 2013). The X-5 has a pusher configuration, with the propeller mounted at the back of the airframe. A 1,300-kV motor was selected to power the vehicle. A motor with this output was chosen due to its ability to provide adequate thrust without compromising flight time.

The airframe was equipped with an Ardupilot autopilot, which allows for autonomous and manual control of an aerial vehicle. Control is maintained through the manipulation of servos for steering the plane and motor control for adjusting throttle. The level of control exerted by the autopilot is determined through tuning parameters associated with the autopilot's internal proportional-integral-derivative controllers. These controllers provide turning settings for yaw, pitch, roll, and throttle gain and cross-track behavior. Telemetry is sent from the vehicle to a laptop running the free and open-source Mission Planner software. The Mission Planner software allows for the preprogramming of flight patterns; the ability to monitor position, orientation, and heading of the air vehicle in real time; and the analysis of detailed flight logs post hoc. During operations at the site, flight plans were developed in Mission Planner and flashed to the Ardupilot hardware installed on the air vehicle. Modifications were made to the interior of the X-5 to accommodate the configuration of components and a compact point-and-shoot digital camera (Canon ELPH 300 HS). Assembly of the UAV required about two weeks of part-time work (though this assembly time can be reduced significantly with subsequent builds). This vehicle was quite inexpensive: $570 in total, including the airframe ($70), autopilot and GPS ($250), and flight hardware ($250). With a redundant airframe, radio transmitter/receiver, and spare parts, a field-ready system can be assembled for about $1,100.

FIGURE 6. Launching the Skywalker unmanned aerial vehicle, 2013.

Test flights were conducted in an area of rural Tennessee farmland at an elevation of approximately 274 m asl. After four launches, the aircraft's parameters were tuned sufficiently to allow controlled flight. The X-5 achieved controlled flight for both fully manual (operator possesses full control of the vehicle using the remote control) and guided (the autopilot is utilized to stabilize the vehicle) control modes. The X-5 is shown flying shortly after a hand launch in Figure 6. Test flights with the aircraft were relatively straightforward. After a short process of tuning control parameters, stable flight was achieved for manual and autonomous control modes.

Numerous test flights were conducted at Mawchu Llacta to determine ideal launch parameters. Initially, the configuration used at Mawchu Llacta was identical to that used at the Tennessee site; however, the vehicle was unable to generate the thrust necessary for a successful takeoff. Despite modifications to the plane's throttle parameters, the vehicle was unable to generate the thrust necessary for takeoff and climb. With further modifications, including propellers with more aggressive pitch, and revised throttle parameters, the UAV eventually generated sufficient thrust to take off and climb in the cool conditions of the early morning hours in this high-elevation context.

Once takeoff and climb performed reliably, attention was turned to achieving stable straight-line flight. The vehicle frequently experienced uncontrolled rotation during flight, even after resolving the thrust issues. Several attempts were made to resolve these adverse yaw and roll effects, with review of output logs after each failed flight.[4] Despite multiple failed flights and servo roll adjustments, no configuration provided more stable tracking (Hooten et al. 2014). Ultimately no attempted combination of these parameters resulted in sustained, stable flight, and no aerial imagery of the site was captured with this vehicle.

Meteorological Balloon (2013)

Undeterred by our UAV woes, the team moved to a meteorological balloon-based aerial imagery capture system. The system is simple in concept: after estimating the volume of helium required to lift a payload of approximately 750 g at 4,100 m, we outfitted a large (9-m^3-capacity) latex meteorological balloon (purchased online for $100) with two nylon (kite line) tethers, from which the Canon ELPH 300 HS camera was suspended via a simple Picavet-based rigging (see Figure 7). Black kite line was used to reduce its visibility in photos. Two lines and operators enabled greater control, minimized the length of the tethers visible in image frames, provided fail-safe redundancy, and enabled an approximate nadir camera orientation through the use of the Picavet (see Mozas-Calvache et al. 2012 for detailed description of a similar system). The camera firmware was reflashed using the Canon Hack Development Kit, and the kit's intervalometer script was used to set a 10-second shooting interval. We calculated a minimum height of 15 m to capture a diagonal view distance of 12 m (given the viewing angle of the camera lens). With the balloon aloft at this approximate height, the balloon operators then walked over the breadth of the site in a lawnmower pattern as the camera captured images at 10-second intervals.

Over the course of three workdays, the field crew captured 2,414 usable images of the site, covering virtually its entire urban grid (see resulting orthomosaics and other data products below). Obtaining the imagery was difficult work. A sufficient supply of helium for at least three refills was required, and helium tank options in this region of Peru are limited. The only feasible option was a large steel helium tank weighing 90 kg, which had to be carried up to Mawchu Llacta (the risk of bursting the balloon on a tree or other obstacle on the hike to the site was

FIGURE 7. Aerial survey with meteorological balloon, 2013 (photo by Scotti Norman).

deemed too high). Once the balloon was inflated and aloft with the camera rig, site walk over was complicated by the many high fieldstone walls and other obstacles (e.g., a high-elevation marsh runs through the center of the site). The tethers had to be relayed between team members as these obstacles were negotiated, resulting in redundant and oblique images. Winds generally pick up in the late morning hours and continue through the afternoon. Even moderate breezes tended to sway the balloon and camera rigging, which also resulted in oblique and blurry images. The balloon ultimately ruptured during the fourth day of work at a neighboring site, probably owing to repeated reinflation and the jostling of the wind.[5]

Despite these challenges, this method proved highly effective overall. Through balloon-based aerial photography, sufficient imagery was obtained to produce virtually full-coverage, high-resolution orthomosaics and 3-D models of Mawchu Llacta.

PHOTOGRAMMETRIC PROCESSING

Photogrammetric processing of raw imagery enables the production of planimetrically correct orthomosaics and the production of a variety of 3-D meshes, digital terrain models (DTMs), and DEMs via SfM software. As discussed previously, the project chose Agisoft PhotoScan for this task, based on its advanced image alignment and SfM algorithms, automated work flows, and intuitive graphical user interface. However, photogrammetric processing requires significant computational power. Random access memory and video random access memory capacity is especially important, followed by central processing unit capacity and hard drive type (solid state vs. disc-based, read/write speed, etc.). Laptops with dedicated CPUs and large RAM capacity can process small- to medium-size photogrammetric chunks in a few minutes. Larger batches of images ("chunks")-those exceeding 100 images, more or less—require either considerably longer processing time or significantly increased computational resources.[6] Depending on image quality and computational resources, photogrammetric processing can be the second potential bottleneck in this work flow.

The steps in the photogrammetric work flow involve selecting overlapping image batches and aligning, geolocating, and orthorectifying the aerial imagery, followed by export to various 2-D and 3-D formats. The first step—selecting image batches—is important and often the most time consuming. This was especially so in our case because the UAV flights from 2012 were manual and irregular and the balloon-based photo series contained many redundant, blurry, and highly oblique images. However, once an image series is selected, the alignment process is very simple. PhotoScan does not require calibration

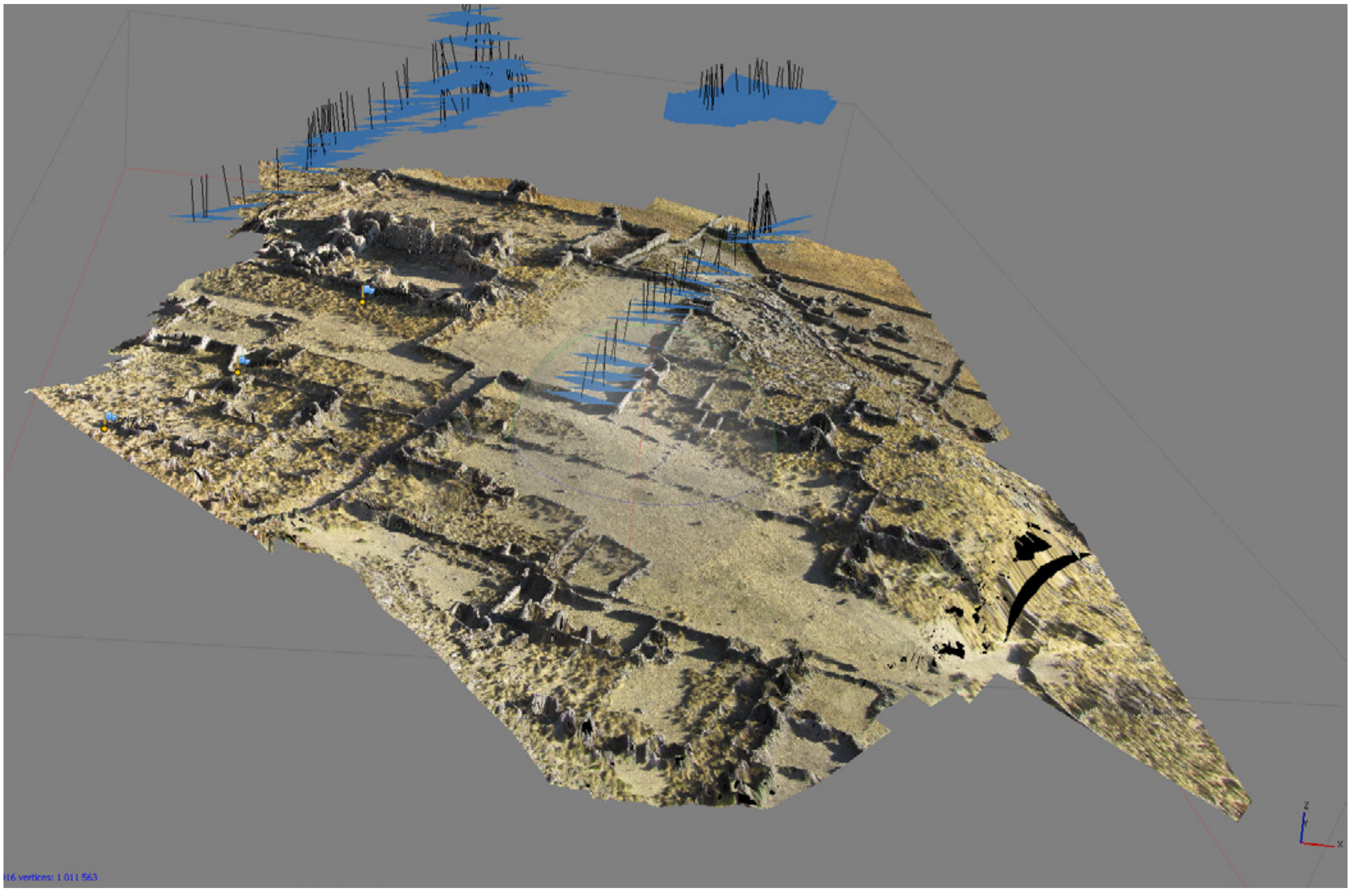

FIGURE 8. Screen capture from Agisoft PhotoScan image alignment and reconstruction of camera positions from balloon overflight.

to camera lens specifications or other metadata.[7] Images are simply selected and auto-aligned. During this process, the program automatically identifies common points between images based on color and texture. From these multiple perspectives of common points, stereoscopy (and thus three-dimensionality) is reconstructed (see Supplemental Video 1). Figure 8 shows an example of how PhotoScan infers relative camera positions and three-dimensionality during the initial alignment process. After this relative alignment, the user sets pin markers in the imagery indicating the locations of GCPs, and the coordinates are entered for each to locate the model coordinate space. Because this is a manual process requiring extensive review of the imagery set, this is the second potentially time-consuming step, depending on the visibility of the GCPs in the resulting imagery. Once GCPs are established, the camera alignments can be optimized, and a 3-D mesh of the surface can be generated. A photorealistic texture (derived from a composite rendering of the photomosaic) can also be generated for overlay on the mesh. At this stage, a point cloud can be exported in a variety of formats (e.g., the .las data set format, which is a common file type for LiDAR data) for later interpolation to DEM in a GIS program.[8] PhotoScan has recently added a set of supervised raster classification algorithms, which enables functionality such as feature extraction (e.g., classification of architectural features) and bare earth DEMs. An orthophoto of the aligned image mosaic can be exported in a number of formats (all georeferenced).[9] This is the base imagery to be used for digitizing features in a mobile GIS (see below).

The results of these processes varied considerably between the 2012 and 2013 seasons. The 2012 imagery produced an orthomosaic of 4-cm resolution covering about one-third (11 ha) of the urban grid of the town. This orthomosaic was derived from the Skate test flights, with the UAV equipped with a GoPro HERO2 camera. Though popular for its compact size and light weight, the GoPro HERO2 is not an optimal camera for photogrammetric processing. Designed primarily for point-of-view video shooting, the GoPro HERO2 uses a very wide-angle lens and a rolling shutter. Optical distortion from the wide-angle lens increases processing time and yields higher error residuals. The rolling shutter is a more fundamental problem, because the sensor surface is not exposed simultaneously but, rather, from one edge to the other. Thus, the sensor is exposed at Time 1 at one edge of the frame but at Time 1 + *X* at the opposite edge. On a fast-moving platform, such as a UAV, the distortion introduced can be nontrivial. These distortions are appreciable in Figure 9, mostly in the form of slightly wavy features that should be linear. We were aware of these issues with the GoPro HERO2 at the time, but time constraints did not allow us to change out the camera before fieldwork commenced. Our plan to eventually switch the camera for a conventional compact point and shoot was not implemented because of the difficulties we

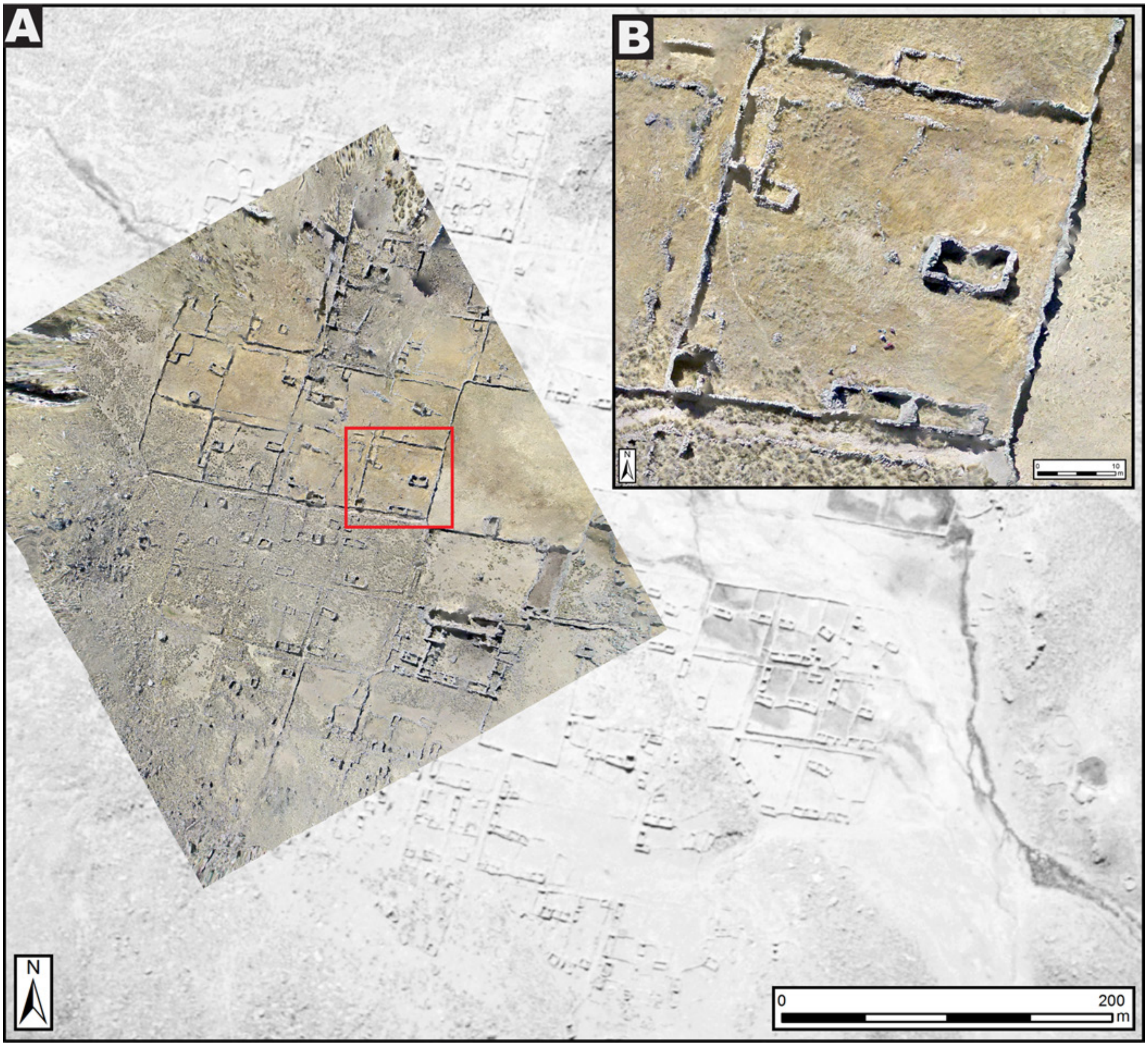

FIGURE 9. (a) Orthomosaic from the Skate unmanned aerial vehicle, based on 800 images; (b) detail. Note the good resolution but wavy linear features, structure obliqueness, and artifacts (blurry areas).

had in achieving stable flight. As is evident in Figure 9, feature detail is generally good, but structures are slightly oblique in perspective, due to a lack of photos from multiple angles. Other "smudge" artifacts are also present in this orthomosaic and obscure many features, which are largely the product of scratches on the lens (from crashes).

The imagery and 3-D DTM from the balloon overflight of 2013 produced far superior results. We experimented with image chunks of varying sizes, seeking optimal resolution and accuracy. This iterative process required several weeks of experimentation after returning from the field but ultimately produced nine overlapping orthophoto and DEM chunks that document a 34-ha area at 5- to 8-cm pixel resolution. As can be appreciated in Figure 10, these chunks provide virtually complete coverage of the settlement area with visible architecture (small voids are due to incomplete overlap between passes during balloon overflight). A 3-D pdf of one of the imagery chunks can be downloaded (Supplemental Figure 1). The resolution of this imagery enables a much richer view of the built environment of this large settlement than is possible via traditional mapping methods. However, direct field observation is required to record architectural details, such as masonry style, wall joins, and features inside structures (e.g., wall niches). Mobile GIS enables this registry.

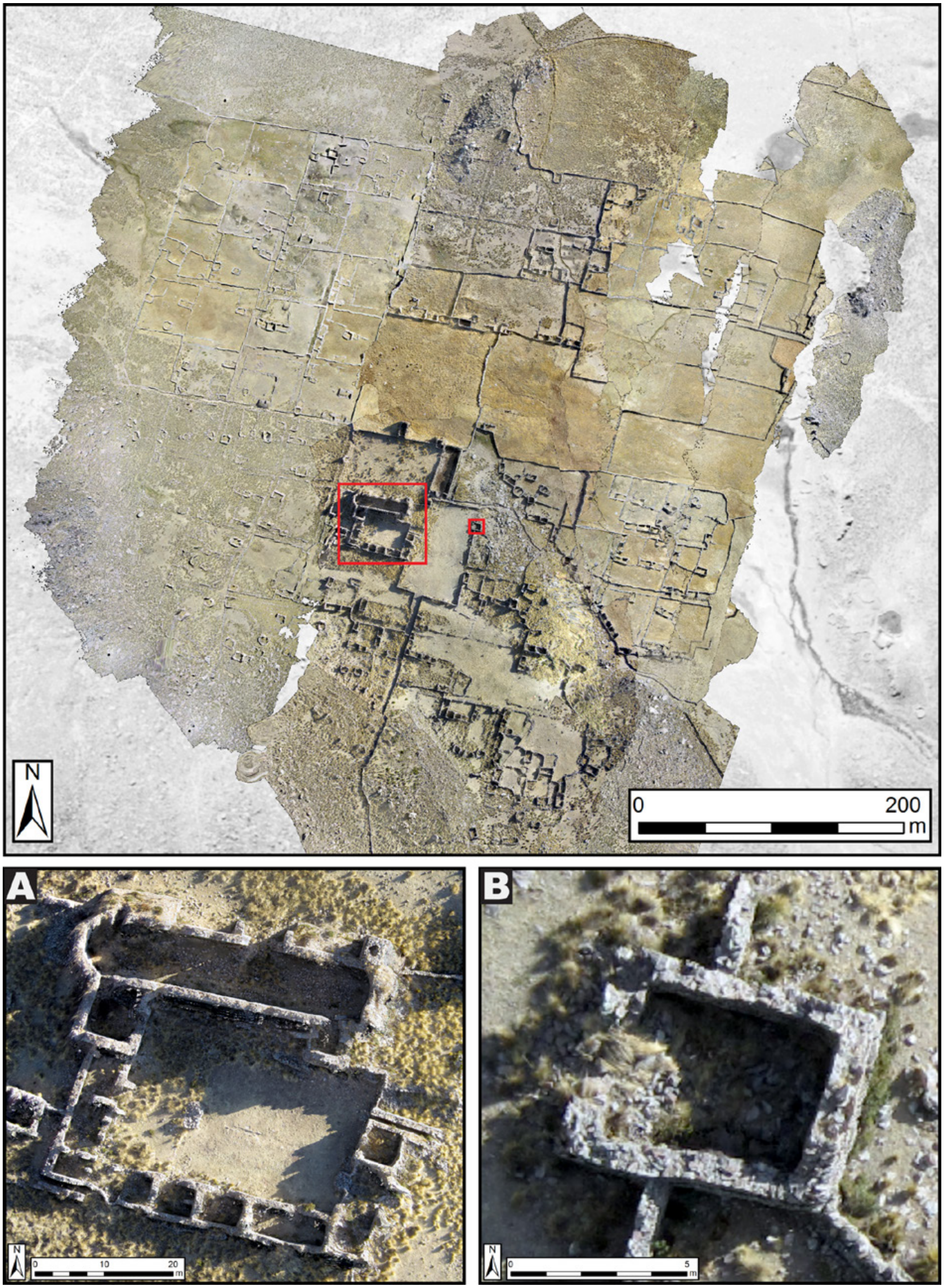

FIGURE 10. Overview of orthomosaic from balloon overflight, based on 2,414 photos in nine chunks. Boxes indicate areas of detail shown in insets A and B.

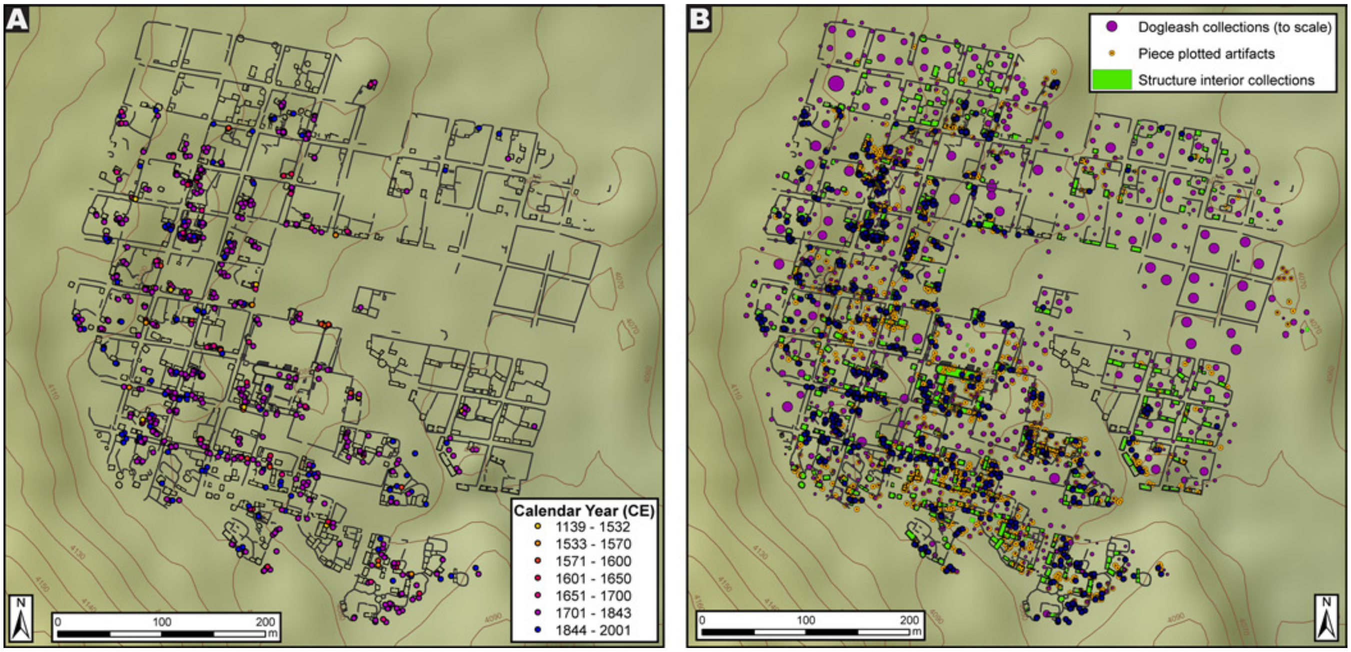

FIGURE 11. Thematic maps using the preliminary architectural base map from orthomosaic digitization: (a) lichenometric dates; (b) artifact collections (ceramics).

FEATURE DIGITIZATION AND ATTRIBUTE REGISTRY VIA MOBILE GIS

This project builds on prior efforts toward developing near-paperless, GIS-based infield data entry in the study area (Tripcevich and Wernke 2010). Mobile GIS has diversified greatly in recent years, moving from the Windows Mobile environment of offerings such as Esri's ArcPad (the mobile counterpart to ArcMap) to a proliferation of tablets, smartphones, and a variety of laptop/tablet hybrids, opening up an exciting range of mobile GIS possibilities for field archaeology. The intuitive touch-based interface of tablets and smartphones greatly reduces human-machine impedances, which not only facilitates the training of nonspecialists but also enriches the range and quality of the registered data. A full review of the growth of this field is beyond the scope of this article, but several new and emerging open-source options are now available, such as the Archaeological Recording Kit (ARK 2014) and the Federated Archaeological Information Management System (2014). A version of the open-source QGIS (2014) for Android is due for release soon.

The now available open-source options were not yet released when we began this project, so we opted for a commercial product, Garafa GIS Pro, an iOS-based mobile GIS for iPad or iPhone (Garafa, Inc. 2013). Generating base maps and attribute data entry forms is very straightforward in GIS Pro, and they can be copied across multiple devices. Data collected in the field are synced via iTunes and imported as themes (e.g., shapefiles) in a GIS program. For this project, we generated a lengthy form for buildings, with 65 attribute fields for recording observations of dimensions and form, materials, style, inferred functions, condition, and other architectural details. Other attribute forms and their corresponding spatial primitives (point, line, polygon) were developed for features, canals, and walls that defined exterior (unroofed) spaces. We also devised forms for intensive surface collections and lichenometric dating, as measurements of lichen specimens (of the species *Rhizocarpon geographicum*) were recorded from each structure for dating purposes.

Four teams (each with two to three members) were equipped with iPads to draft features and record the attribute data. In the ideal work flow, teams would digitize the vector features directly on the UAV- or balloon-based high-resolution orthoimagery. Photogrammetric processing was not finished during fieldwork, however, necessitating the use of lower-resolution air photos. Thus, team members drafted sketches of features and completed the accompanying attribute forms, and the feature geometry was later revised and refined once the orthomosaics were finished. This tablet-based mobile GIS enabled the rapid collection of large, rich data sets, mostly by end users with little or no prior GIS training: the teams mapped and completed attribute forms for all structures (*N* = 562) at Mawchu Llacta, as well as more than 1,000 walls, 107 features, five canals, 686 lichen specimens, and 2,460 artifact collection proveniences (Figure 11). These data were collected during three and a half months of fieldwork between 2012 and 2014.

GIS DATA SYNCHRONIZATION AND MANAGEMENT

Although GIS Pro was simple and intuitive from an end user perspective, data synchronization was a manual task that required considerable administrative effort. It was designed with a single end user in mind, rather than a large collaborative team, and provided no automated data synchronization between teams. We created a binary attribute field to flag new or modified features or attributes, but synchronizing the data into a master GIS nonetheless required a lot of attention to detail from a project administration perspective. New and emerging open-source mobile GIS systems (such as those mentioned above) have built in synchronization to master database functionality.

DISCUSSION AND PROSPECTS

Through the process of testing and experimenting with these aerial and mobile GIS systems, we have worked toward an efficient, accurate, affordable, and analytically rich means of documenting complex, mid-scale archaeological phenomena. The integration of low-altitude aerial photogrammetry and mobile GIS has enabled documentation and analysis at a level of detail that is otherwise very time consuming and expensive to achieve using traditional methods. Beyond the level of detail, the considerable advantage of this approach is the multiple media and forms of representation it produces: vector-based representations in both 2-D (as in a traditional plan view architectural map) and 3-D (as textured DTMs); raster-based, continuous-surface representations via visible-light orthomosaics; and point clouds. What results is a high-resolution 2-D and 3-D repository with rich, geographically coregistered artifact and attribute data. This system can be readily—and likely more easily—adapted to a variety of contexts.

But this project can also be taken as a kind of extreme condition case. The challenges we faced were largely effects of the high-elevation context of the site. Analysis of flight logs indicates that the difficulties in achieving reliable flight with the DIY UAV in 2013 were caused by adverse yaw events, which in turn were an effect of the rudderless, flying-wing design of the airframe. For future field seasons we will move to a new rudder-based UAV airframe with a larger wingspan and greater wing surface area (the UAV Hobby TechPod). With this design, we expect better high-elevation performance. While most research contexts do not present such extreme environmental challenges, even in ideal conditions, working with a UAV requires piloting experience. Systems that promise fully autonomous operation, such as many recent commercial turnkey systems, require calibration and some manual operation at takeoff and landing. In addition to these technical challenges to UAV-based imagery capture, similar or superior results can be achieved with lighter-than-air platforms, albeit with greater investments in field time. Those wary of the technical, budgetary, and (in many countries) regulatory issues involved in UAV flight will doubtless further develop these techniques. Our simple balloon rig can be improved upon with a more refined Picavet suspension system, GPS synchronization with the camera intervalometer, or live telemetry to obtain real-time views from the perspective of the balloon. Semiautonomous or autonomous blimps are another likely option in the near future.

Other bottlenecks in the work flow are more easily addressed: GCP registry with DGPS would speed up that process considerably. Photogrammetric processing is much more efficient and speedy than it was just a year ago, and computational power continues to increase at near exponential rates. The prospects for this kind of approach are very bright and will doubtless continue to expand rapidly. UAV costs are dropping drastically. New designs and better open-source autopilots are becoming available at a remarkable rate. The community of developers and users continues to grow and is beginning to move from an early-adopter-only to a more general user base, as the technology matures and becomes more user friendly. Other sensors, such as infrared, LiDAR, and multispectral instruments, are beginning to be deployed on research UAVs; their use will surely expand as their components are further miniaturized, ruggedized, and economized. Based on these trends, it is likely that within the next five years, UAVs are likely to be very common in archaeologists' tool kits. Given the great gains in efficiency and the quality of the data produced, at a minimum, most projects in the near future will contract such work or perform it themselves. With advances in photogrammetric software, the kinds of techniques applied here will soon be widely applied at the scale of excavation units and features.

In sum, as archaeological patrimony disappears at alarming rates around the world, and as archaeological research is often destructive vis-à-vis its contexts of analysis, archaeologists must continue improving our capabilities to capture the complexity of the archaeological record at all scales. Though we archaeologists may always be "prisoners of space," these fast-emerging methods greatly enrich contextual knowledge and promise to generate virtual repositories of archaeological features, sites, and landscapes.

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Data Availability Statement

Access to the physical and digital data on which this research is based can be requested by writing to Dr. Steven Wernke, the corresponding author, at s.wernke@vanderbilt.edu.

Supplemental Materials

Supplemental materials are accessible via the author's website.

Supplemental Figure 1. 3D PDF of central area of Mawchu Llacta. Download at: http://www.vanderbilt.edu/wernke/download/Supplemental_Figure_01.pdf

Supplemental Video 1. Video of preliminary image alignment in Agisoft Photoscan. Download at http://www.vanderbilt.edu/wernke/download/Supplemental_Video_01.avi

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NOTES

1. Throughout, scale is used in the more commonplace sense of "area represented" rather than the cartographically correct sense of ratio of representation to actual size.
2. During the 2012 field season, we established 53 GCPs, but this proved suboptimal for orthophoto and DEM processing. When in doubt, shooting more GCPs than you anticipate will be needed. Some GCPs may not be as readily visible in the imagery as anticipated in the field. Also, GCPs not used in the alignment process can be used to check the accuracy of orthophoto output (by checking their coordinates in the resulting orthophoto against their known coordinates).
3. Given the importance of precision for GCPs, when shooting GCPs for architectural or other features, best practice is to document the precise location of the point by taking a local photo and/or providing a sketch map of the point location while recording its corresponding GCP code in the field log.
4. Adverse yaw is the tendency of an aircraft to yaw (i.e., rotate about the yaw axis) in the opposite direction of a roll (i.e., rotate about the roll axis), leading to flight instability during turns, making proper control of the vehicle difficult.
5. Though marginally heavier and more expensive than latex, Mylar balloons are stronger and probably a better option overall for fieldwork in challenging conditions.
6. We opted to take a full-size server, equipped with two quad-core Intel i7 processors, 88 GB of RAM, and solid-state operating system drive to the field for photogrammetric processing. Even with this much computational power, jobs with many hundreds of photos required hours to process. Subsequent updates to Agisoft PhotoScan have greatly improved resource efficiency, cutting that processing time by at least half.
7. Coordinate positions of the camera for each photo can be specified within PhotoScan, and this information will accelerate the alignment process. Our balloon-based system did not include a GPS. In a UAV configuration, synchronization of GPS and camera would enable such functionality and processing efficiency.
8. PhotoScan can also export DEMs. However, the interpolation algorithms are limited, and it uses the vertices of the 3-D mesh, rather than the original point cloud from the image alignment process.
9. Chunks can also be merged into larger models and orthomosaics before exporting.

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