CHAPTER 9: INSIDE THE WORLD'S LARGEST DRONE ARCHAEOLOGY PROGRAM

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One overcast day in April 2015, Aldo Watanave took the train to Machu Picchu.[1] Watanave had with him an eight-rotored drone, which he planned to use to photograph a stretch of the well-trafficked tourist road leading to Machu Picchu. From those photographs, Watanave would create a contour-line map. This map would help engineers determine the placement of a new museum, slated to be built away from the current road.

Watanave and his colleagues from Peru's Ministry of Culture arrived in Aguas Calientes, the rail terminus nearest Machu Picchu. From an open spot near a busy road bridge over the Urubamba River, which rushed about 10 feet below, Watanave launched the team's DJI Spreading Wings S1000 octocopter, a $1,999 commercial off-the-shelf drone. Watanave would pilot the drone while another team member controlled the camera.* A third colleague followed the drone on the ground with a surveying system,† which he used to gather GPS coordinate information that they would later cross-reference with the photographs to create a geographically accurate map.

Watanave flew the drone over the bridge using a first-person view system that allowed him to see real-time video footage from the drone on a small monitor. He was about halfway done with the mapping when the drone's battery ran low; he landed it to swap in a fresh battery. As he launched the drone again, a French tourist, disturbed by the aircraft, started shouting at him. The shouting distracted Watanave, who gasped as the drone came precariously close to a nearly invisible power line strung over the road. He tried to navigate away, but the drone took a sharp turn to the right, neatly clipping a propeller on the power line. Now impossible to control, the drone veered to the left at high speed, plummeting into some bushes on a ledge above the river.

The road to Machu Picchu was just one of hundreds of sites that the Peruvian government archaeologists had mapped since the drone program at the Ministry of Culture began in August 2013. The team mapped 180 sites in 2014, and had managed to map 222 more by June 2015. As Peru is estimated to harbor about 100,000 archaeological sites, according to government sources, the drone team has thus far focused on smaller sites and on those at particular risk of being damaged in the wake of Peru's current housing boom.

The scale of the experiment, says program founder Dr. Luis Jaime Castillo Butters, proves that collecting useful data with a drone requires neither unique technical skill nor a particularly huge budget. The team's success, he says, stems from their determination to keep flying as often as they can, despite inevitable setbacks. "We're not experts.

* A Sony NEX-7 24.3 MP camera mounted on a DJI Zenmuse Z15 gimbal

† Trimble R8 GNSS System

Observation huts on the outskirts of Machu Picchu, Peru's most popular tourist attraction. (All photographs in this chapter are by Faine Greenwood)

We don't build drones, we don't build engines, we don't build anything," Castillo explains. "We simply use this technology—but we use it a lot."

The Ministry of Culture's UAV mapping efforts haven't gone unnoticed by other branches of the Peruvian government. The UAV team recently assisted Peru's Superintendencia Nacional de Bienes Estatales (SBN), which regulates state assets, with mapping a nationally owned beach that was being encroached upon by private development. The SBN, says Watanave, was able to use the drone imagery to document places where private homes had been built illegally—information that can be used to more effectively enforce the rules. The agency is now considering a drone program of its own.

Castillo, an archaeologist who served as Peru's vice minister of cultural heritage from 2013 to May 2015, came up with the project when he was a professor at Lima's Pontificia Universidad Católica.[2] Castillo has been excavating on Peru's northern coast for 25 years. He's long been a proponent of using new technologies to study pre-Columbian cultures. In his lab at the university, Castillo had been involved in a project using X-ray fluorescence spectrometry to analyze the chemical composition of ancient pottery.[3] That analysis could pinpoint where a particular pot came from, determine what it was used for, and ferret out forgeries.

Castillo began contemplating the potential of UAV technology for archaeology in 2011, when he began a year-long stint as a fellow at Dumbarton Oaks, a Harvard research institute in Washington, D.C. Steve Wernke, an archaeologist at Vanderbilt University in Nashville, had already been flying drones in the Colca Valley of southern Peru, and Castillo became intrigued by Wernke's efforts. While still in Washington, Castillo purchased a Parrot AR drone for $300 from Radio Shack, familiarizing himself with the controls. He returned to Peru, and in April 2013 decided to purchase a drone in a joint effort with Jeffrey Quilter, a Harvard archaeologist. Castillo bought two DJI drones: a Spreading Wings DJI S800, designed for professional photography and video work, and a cheaper DJI Phantom 1. During the summer of 2013, Castillo and Watanave—who had come to study under him in Lima—first learned to fly the two drones, then how to tinker with them to do archaeology.

At El Tigre mountain, in the Amazonas region of northern Peru, they used the Phantom 1 to photograph 23 previously undiscovered sarcophagi belonging to the pre-Incan Chachapoyas culture,[4] saving them the trouble (and potential danger) of climbing the high cliffs where the artifacts had been placed. They also began to develop a method of using the larger DJI S800, equipped with a Sony Alpha NEX-7 mirrorless camera, to create photographic maps of some of the archaeological sites they worked on.

When they started, the small team of drone specialists had plenty to learn. The team, Castillo relates, seriously overpaid a local specialist to assemble the DJI S800, which Castillo brought back from the U.S. in its component parts.

Aldo Watanave with an S-1000 drone at the Pisaq archaeological site

A local UAV specialist claimed he would teach them to fly but seemed loath to give up the controls. Castillo eventually lost his patience. "I told the guy, 'You know what, even if I crash the damn thing, I'm going to fly it—because this is why I bought it,'" he remembers. "That bring us to one point I consider to be important: being independent, having the capacity to do your own stuff."

Watanave and Castillo tweaked the DJI drones to suit Peru's often difficult field conditions. They built their own sand-resistant gimbal for the S800 and swapped out the GoPro camera that came with the Phantom 1 for a lightweight point-and-shoot Nikon camera, to remove the distortion that the GoPro's extreme wide-angle lens introduced.

With these modifications in place and with increasing confidence in their flying ability, Castillo and Watanave were able to begin their experiment in 3D drone mapping in earnest, heading to the north coast of Peru and flying the devices on a daily basis. In August 2013, Castillo was appointed Peru's vice minister of cultural heritage, and he brought the drone program with him, setting up his UAV laboratory inside the Ministry of Culture building. By the end of 2013, the team was making new drone maps weekly.

Peru places great stock in its archaeological heritage, and some sites are particularly beloved by foreign visitors.

Peruvian officials estimate that over 3.8 million foreign tourists will arrive each year by 2016. The travel and tourism sector makes up a significant part of Peru's GDP: A 2013 World Economic Forum report found the direct contribution of the sector to overall GDP came to 3.4 percent, and was as large as 9 percent when indirect contributions were considered.[5] These tourists will arrive in a country that had just begun to experience an economic slowdown as of 2014, after a period of rapid growth averaging 6.4 percent per year from 2003 to 2013.[6] Peru's poverty levels are also dropping, to 22.7 percent in 2014 from 30.8 percent in 2010.[7] While the expanding economy has bolstered the spirits of investors and consumers, it has also ushered in a boom in construction and development, as Peru's increasingly prosperous population demands more and better housing.

Archaeologists are well aware that increased demand for housing can have dire consequences for archaeological sites in areas ripe for development. Sometimes the results are particularly embarrassing. In June 2013, a 4,000-year-old pyramid at the El Paraiso ruins near Lima was destroyed by two private construction companies, Alisol and Provelanz. Police had to intervene to stop the company from destroying three more pyramids.[8] The incident, which made international headlines, was a reminder to Peru's government that it lacked important information on the boundaries and dimensions of its many archaeological sites. While thousands of sites were in the Ministry of Culture's databases, the ministry lacked precise visual information, making it difficult to determine which places were being threatened by development. There was also the problem of tracking damage that had already occurred, a process that Castillo and Watanave say was difficult with imagery captured only from the ground.

Given the lack of accurate and legally useful data about the exact boundaries of these archaeological sites, developers could easily claim ignorance if they built over a site, insulating them from criminal consequences. Drones, Castillo realized, might be able to help. Since Castillo established his team in 2013, it has expanded to eight staff members, including pilots, drivers, and computer technicians. Castillo has also opened regional offices in Cusco and in northern Peru, each with its own stock of drones. The team now has seven DJI S1000 octocopters and 33 small DJI Phantom quadcopters, with an annual budget of about $150,000, Castillo says.

Watanave travels the country and trains new drone pilots and aerial imagery specialists within these regions, adding to the pool of capable Peruvian UAV specialists. The easy-to-fly Phantom 2s are particularly popular among archaeologists new to UAV flight, who use them to shoot video and general overviews of the sites they work on.

The drone team says they've mapped more than 500 sites in the past two years, a considerable improvement over slower ground surveying techniques. The UAVs have also spared them the cost of hiring pilots to fly manned photography missions. With the assistance of GIS (geographic information system) tools and Agisoft PhotoScan software, the raw imagery is used for a variety of archaeological applications—from simple documentation to damage and threat assessment. Besides doing science, the team hopes to educate the public by using drone images. They add the imagery they collect to the ministry's existing geographical and georeferenced database of archaeological sites, known as SIGDA (Sistema de Información Geográfica de Arqueología). The group hopes that the resulting 3D maps and photographic data will be freely available to the public sometime in 2015.

When working with the DJI S1000, Watanave says, it takes the team about 10 to 20 minutes to fly over and satisfactorily photograph a hectare of land (2.47 acres), subject to variables including wind speed, weather, and altitude. In a good week, he reports, the team can map four sites a day. The mapping UAVs have been equipped with Sony Alpha NEX-7 mirrorless cameras, which have 24.3 megapixel sensors and swappable lenses. The archaeologists typically set the cameras to an aperture of f/6.3, which gives them deep depth of field, and use the camera's automatic features to select a shutter speed between 1/200th and 1/600th of a second, fast enough to minimize the blur induced by the drone's motion. The camera is fired off every two to three seconds by either an automatic timer or remote control in order to shoot enough images to create orthomosaic (geometrically corrected) maps and three-dimensional models.*

The team flies the UAV at a relatively low altitude during their mapping missions, usually between 70 and 100 meters (230 to 328 feet) above ground level, depending on the size of the site and the ground resolution they want to achieve. With the focal length of the NEX-7 camera's lens set at 16 mm, Watanave says, they are able to achieve a ground resolution of 1 to 1.5 centimeters per pixel at an altitude

* Most drone mappers prefer to take pictures at automatic intervals, but Watanave says he likes to use FPV (first-person view) video to align his pictures.

Members of the Peruvian drone mapping team check battery levels before flying over the road leading to Machu Picchu.

of 70 meters, which drops to 2.1 to 2.3 cm per pixel at an altitude of 100 meters.

Mapping is constrained primarily by the brief battery life of multi-rotor UAVs, which are less mechanically efficient than airplane-like fixed-wing drones. The DJI S1000 octocopter is able to fly for only about seven to 15 minutes, while the smaller DJI Phantom models can fly for a notional maximum of 25 minutes. (Endurance for both models depends on the weight of the payload, but the smaller quadcopter generally can stay in the air longer.) Flight time is also dependent on altitude: At lofty sites in Peru's mountains, it is harder for the UAV motors to function, cutting operational times by about half.

The ministry's interest in collecting 3D information about structures is one reason why it currently uses only multi-rotor UAVs, with their shorter battery lives, instead of longer-flying fixed-wing UAVs. "The advantage of the [multi-rotor] drone if you are going to record the buildings is that the drone hovers … It doesn't just take pictures from above, what we call 'sentinel' [vertical] pictures. It also takes lateral pictures," Castillo explains. "When you can create a 3D model, you can show people where the excavation should be done," says Watanave, explaining the technique's benefits over more traditional 2D mapping practices. To create a 3D map, the UAV is flown over the site with the camera set at a vertical or "sentinel" angle, while a second pass over the site is flown with the camera at a 45 degree angle. The two perspectives are then combined in Agisoft PhotoScan processing software, which uses GPS data to create a georeferenced and spatially accurate model. With 3D data, the archaeologists can create maps that show multiple sides of a single building, carry out accurate measurements, and assess the volume of the site—permitting them, for example, to better anticipate where water might pool in a given ruin or determine where illegal digging has taken place.

Though the cameras take high-resolution images of the scenery below, the resulting images don't have a GPS frame of reference, which must be added to create a geographically accurate map. While some UAV mappers use GPS coordinates taken from cameras or onboard GPS loggers to record the location where each photo was taken, the archaeologists need to create maps with centimeter-level precision for the demands of their scientific research and to properly record the boundaries of each archaeological site. (The GPS information from the camera specifies, with some margin of error, the position of the camera itself at any given time, but does not unambiguously locate points in the image.)With geographically accurate data, the maps make a better case for a given site's exact location—another deterrent to illegal but hard-to-catch encroachment.

To achieve this level of geographical accuracy, the Ministry of Culture's UAV mappers take ground control points, which are accurately surveyed locations that can be used as a reference for the entire map. Using a Trimble R8 GNSS (global navigation satellite system) ground surveying system, which can measure position to within 1 cm accuracy, the team collects multiple ground control points in the area they intend to fly over. After the flight is over, the ground control points are entered into Agisoft PhotoScan processing software, which uses them to accurately render the map.

IMAGE PROCESSING

First, the researchers enter their images into Agisoft PhotoScan, which will process them into a textured 3D model, which can then be converted into a georeferenced two-dimensional map, or orthophoto.

The team enters these maps into the Ministry of Culture's archaeological database. Researchers can use the database to create other types of maps and models , such as contour maps, digital elevation models, and digital terrain models. The resulting data can be used to infer which portion of a site might be likely to collapse soon, or where potentially damaging water tends to collect inside weakened walls.

The 3D data, with its added spatial information, can be an aid to exploration. Ministry of Culture researchers have already used the 3D maps to identify new places to dig, including a site in downtown Lima, Huaca Mateo Salado. The site comprises five monumental and crumbling pyramids, some parts of which date to 1100 B.C. The eroding, earth-colored stone of the site rubs shoulders with single-family homes and a busy roadway.

Large sites can take hours to process, even with the relatively powerful workstation computers in the Ministry of Culture's laboratory. A model with 300 images takes three to four hours to process in Agisoft PhotoScan with the laboratory's computer, which has 32 GB of RAM and a 4 GB graphics card. The resulting files can be as large as a gigabyte, with most averaging around 600 MBs. The team is working to resolve this issue of size—to accomplish its goal of making the files available to the public online.

"From my stance and for my purposes, I think we should have this as open-source, open public data," says Castillo, who hopes the ministry can launch a publicly available database of 3D-mapped archaeological sites sometime in the summer of 2015. "They can download the raw data, and build their own models, and start working with the sites for their own purposes."

Preventing people from encroaching on archaeological sites has become a major priority for the Ministry of Culture's UAV program. Although the program was initially conceived of primarily as a recording project, the drone team soon realized that the imagery was catching some abusers of archaeological land in the act. "Always, when we fly the drone over an archaeological site, we catch people who live in the site, or throw garbage inside the site, or we see homeless people living inside the archaeological site. It's terrible," Watanave says. As an example of the type of abuses the imagery can catch, Watanave cited a high-

AUTONOMOUS VERSUS MANUAL FLIGHT

Many UAV mappers use autopilot software to fly drones semi-autonomously. But Castillo and Watanave prefer to fly their aircraft themselves. Weather shifts quickly and software is unreliable, they say, and they often lack the large takeoff and landing areas required by a fixed-wing UAV. They keep their UAVs in their sight at all times, allowing them to anticipate trouble and react more quickly if there is a problem.

"We see the thing at every point, and we can control it," says Castillo. "If anything goes wrong, we can actually try to do something about it. When you fly a fully automatic mission, you are brainless. It comes down, and hopefully, you can recover it. These things fail, they always fail. You have to be ready to take the punch."

The team learned that lesson the hard way at the end of 2014, when a DJI S800 EVO mapping UAV was being flown autonomously over the dusty Huaca Mateo Salado archaeological site in Lima's leafy and heavily residential San Miguel district. While in the middle of a flight, the drone lost communication with its GPS points, flying erratically and eventually crashing near the homes and businesses that surround the pre-Hispanic pyramid. It was a nerve-wracking experience for the team, who take great pains to avoid flying drones too close to other people or non-archaeological structures.

"It was strange because the GPS points inside the computer were excellent, but in one moment, the GPS was lost," Watanave says of the incident. He has never figured out the exact cause of the GPS failure, but ever since, the team hasn't used autonomous navigation for their mapping flights. They repaired the drone, but don't use it much. However, Watanave says he is open to experimenting with it again as the systems improve. -Faine Greenwood

resolution map of the Huacoy archaeological site, on the Chillón River north of Lima, which is estimated to date to 500 B.C. Newly built homes are encroaching upon the crumbling and ghostly structures of the site—the exact kind of development the Ministry of Culture hopes to prevent.

"People say to us, 'We are poor, we don't have land for our house.' But it's not poor people doing this," Watanave says of the encroachment, pointing out that the aerial imagery revealed swimming pools behind high walls. "People aren't satisfied with having a piece of land that sits next to a site. They decide the site is also mine, and they start cutting and building the stuff there," Castillo says of the encroachment the drone imagery has captured. Frustratingly for the archaeologists, simply documenting an encroachment isn't enough to stop it. Some people have lived at the site for years and can't realistically be asked to leave. In other cases, there's simply little way to stop the damage.

It is clear that high-resolution drone imagery isn't enough to protect archaeological sites. Enforcement of government rules against encroaching on or damaging archaeological sites has to accompany better data. That's an uphill battle, acknowledges Castillo, as both large businesses and individual landowners come into conflict with cultural patrimony, and as investors—both national and foreign—claim that an increasing amount of red tape is harming their investments in Peru.

However, it's not only illegal builders that are at risk of being caught by aerial imagery. Greenpeace, the international environmental group, found itself under scrutiny from the Ministry of Culture's drones in December 2014, when members of the organization unfurled a pro-sustainability banner near one of the massive and enigmatic Nazca Lines, which are visible only from the air. Unfortunately, the Greenpeace members were unaware that the soil near the huge etchings in the earth is extremely delicate.

Many Peruvians were outraged, not least Castillo, who arranged for one of the Ministry of Culture's drones to fly over the area to assess the damage. The aerial footage, which showed damage from the banner and from Greenpeace members' footprints in the soil around the geoglyph, was broadcast on the PBS "NewsHour" television program in the United States.[9] Greenpeace Executive Director Kumi Naidoo traveled to Lima to apologize. "I came to Peru in the wake of the Nazca Lines activity to offer my full apologies to the people of Peru and all of those who have been shocked and offended," Naidoo said in a December 2014 press release on the Greenpeace website.[10] "This activity showed Greenpeace in a terrible light. It is simply not what Greenpeace is," he added.

Castillo hopes that the drones will be able to serve as a deterrent to businesses and individuals that in the past might have been able to get away with the illegal destruction of archaeological sites, secure in the knowledge that there was no effective way of documenting their activities. "If we catch them, we can put them in such hot water that they start losing money by the bucket," Castillo says.

The Ministry of Culture's UAV project continues to expand its scope, with plans to map larger areas using a long-range fixed-wing UAV. At the time of this writing, the ministry was considering acquiring a $25,000 SenseFly eBee mapping UAV, which could be used to more effectively map some of Peru's largest and most iconic sites, such as the ruins at Machu Picchu and the extensive adobe remains of Chan Chan in northwestern Peru, the largest pre-Columbian ruin in South America.

As of June 2015, the Ministry of Culture's drone program seemed likely to continue into the future, with government backers recognizing its success and relatively unique nature. In May 2015, Castillo left government and returned to the university. Watanave, who has remained with the ministry,

is confident that the UAV program and the laboratory will receive funding to continue its research and field mapping efforts Castillo, for his part, is now advising the ministry on the creation of a new technology center in Cusco, which will use new methods—including but not limited to drone mapping—for archaeological research. Castillo and Watanave are contemplating how UAVs can be used beyond mapping work. It's possible to use specialized UAVs to create indoor images and videos, a notion that inspired Castillo to recently buy a DJI Inspire 1 drone, a high-end filming tool with relatively sophisticated sense-and-avoid capabilities.[11]

Castillo thinks it would be possible to fly the drone inside certain historic locations, such as Peru's wealth of colonial churches. Castillo and Watanave hope to eventually use the Inspire 1, or a drone like it, to create detailed photographs and perhaps even three-dimensional maps[12] of the interior of these structures. These could be used for archival and research purposes, and to create immersive educational tools for the public.

Castillo is pursuing other experimental work using drones as well, including a recent project using synthetic aperture radar and UAV technology to collect more detailed 3D images of the Nazca Lines. "The more we work, the more applications we find for UAV mapping, for things we hadn't even thought about," he says. "Anybody can work with the drones," Castillo notes. "We are simply doing it on a scale that is actually having a real impact on cultural patrimony."

After Watanave's octocopter crashed on the road below Machu Picchu, he and several colleagues scrambled up the slope to find it. A train sped by on a bluff above them as they located the crash site. To their considerable relief, the drone was quite salvageable: a broken arm, some snapped-off props, and some other minor damage. The drone could be repaired in Lima without too much trouble. Watanave and his drone would fly again. §

Members of the Peruvian Ministry of Culture UAV mapping team looking at their drone as it maps Pisaq, an archaeological site in Peru's Sacred Valley.

ENDNOTES

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