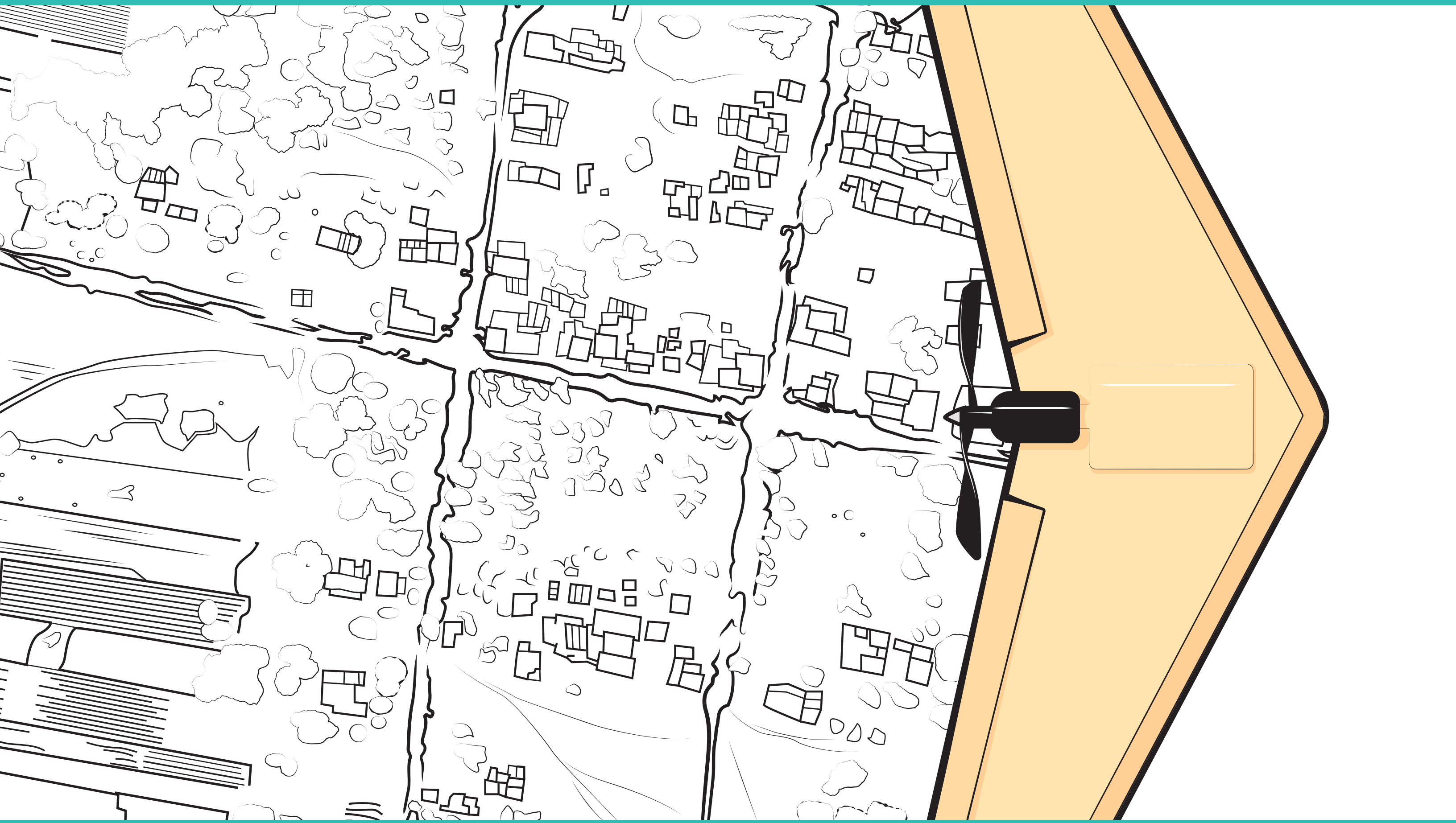
NEW AMERICA



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DRONES AND AERIAL OBSERVATION: NEW TECHNOLOGIES FOR PROPERTY RIGHTS, HUMAN RIGHTS, AND GLOBAL DEVELOPMENT

A PRIMER

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ABOUT NEW AMERICA

New America is dedicated to the renewal of American politics, prosperity, and purpose in the Digital Age. We carry out our mission as a nonprofit civic enterprise: an intellectual venture capital fund, think tank, technology laboratory, public forum, and media platform. New America was founded in 1999 to nurture a new generation of public intellectuals—scholars, policy experts, and journalists who could address major social, economic, and political challenges in ways that would engage the public at large—and to provide a set of blueprints for American renewal in an era of globalization and digitization. The initial challenge, which continues today, was to find the minds and foster the debates needed to guide American renewal in an era of profound, exhilarating, but often threatening change.

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Of course, responsibility for any mistakes rests with the authors alone.

FOREWORD

The recent rapid rise of Unmanned Aerial Vehicles (UAVs)—or drones—has generated equal parts excitement, fascination and consternation from all sectors on all sides. Previously the sole domain of the military and a very few committed hobbyists, drones have exploded onto the public consciousness with images of breathtaking mountain summits, daring search-and-rescues, spectacular crashes, and acrobatic pizza deliveries. By 2024, the industry is projected to reach about $11.5 billion annually. All but unheard of just four years ago, drones are now here to stay.

While non-military, non-commercial uses of UAVs are now, and will probably remain, a small fraction of overall drone activity, given the potential applications—and consequences—it is imperative that all public inquiry, debate and consequent policy making be as thoughtful and well informed as possible. Yet, given the speed, diversity and intensity of drone proliferation and ongoing innovation, it has been difficult to get a comprehensive, global understanding of this fast moving, far-flung landscape.

We hope that this Primer will serve as the first step in a thoughtful, deliberative, fact-based dialogue on how UAV's can make the world a better, safer place. Putting military usage aside, we realize that there are no easy answers to the myriad of regulatory, policy, privacy and appropriate usage questions that have emerged in the last few years regarding drones. Omidyar Network, in partnership with Humanity United and New America, is eager to identify and promote those conditions that maximize the positive externalities of drones while mitigating the negative.

This Primer emanated from the Property Rights Initiative at Omidyar Network, where we appreciate how transformative aerial and satellite mapping can be in lowering the cost and complexity of defining and maintaining property rights, as well as resolving entrenched conflicts and systematically empowering individuals and communities. UAVs hold out the promise of even lower costs and easier use in defining and maintaining property rights.

While drone imagery does require some degree of knowledge and basic resources to use effectively, it can be controlled and owned by users themselves, unlike more expensive satellite and aerial imagery, thereby providing immense opportunities for empowerment. A modestly-priced UAV (< $600 USD) is sophisticated enough to produce timely, high-quality and cloud-free imagery, which can, in turn, be used to define land and property rights, as well as other broader community uses, including community boundary definition, land use planning, accurate population censuses, and the inventory and management of natural resources. Even easy-to-use, no-cost mapping platforms like Google Earth, which have been used to amazing effect by civic groups like Transparent

Chennai for counting previously ignored slum populations, still require ready access to the internet, and rely on the provision of satellite data by third parties which are often out of date and can be obscured with clouds. The traditional information asymmetry is starting to crumble; previously disenfranchised and disadvantaged populations are finding the wherewithal to define and claim their rights.

Not surprisingly, governments worldwide are wrestling in real time with exactly how to react to this democratization of technology and information, particularly in the areas of surveillance and privacy. This is where smart, informed public policy is especially critical. It is imperative that we balance the rights of citizens with legitimate privacy and security concerns. The only way this will happen is if we set up an open, fair and transparent exchange of ideas—something we hope that this Primer will enable.

Similarly, drones provoke another tricky question: Who "owns" the air? Law and public policy have yet to catch up with drone technology in this regard. There is a huge swath of space between 83 feet and 500 feet that still remains unclaimed and undefined. Innovative companies like Amazon and forward-looking public institutions like the Swiss postal service are hoping to fill this void but need this "right of way" to be defined. Likewise, there is an emerging class of "drones for good" that is delivering vaccines to the last mile, uncovering mass atrocities, helping communities recover from natural disaster, keeping governments honest, and saving endangered species. The potential is enormous, and this is only the beginning.

We look forward to engaging with the global community in a measured, even-handed conversation on how we parse the legitimate ethical and legal considerations that drones have uncovered. The promise that they hold for property rights alone is worth the effort. Formal recognition of property rights is essential to the economic security of individuals and communities—and foundational to their economic empowerment. UAVs directly tackle one of the most recalcitrant barriers to property rights—the lack of access to formal systems to register and safeguard property rights. By lowering the cost and complexity of aerial mapping property rights, drones can literally put entire communities on the map, enabling them to be counted and formalized so that they can assert their rights and determine their own destinies.

Peter Rabley

Director, Property Rights

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EXECUTIVE SUMMARY

In a remark that is frequently quoted, a character of Ernest Hemingway's said that he went broke in two ways: gradually, and then suddenly. So too with drones. Their evolution as a technology has a long history—as long, really, as there has been powered flight. Yet it is an evolution that until the last decade had borne only limited fruit. Militaries around the world experimented with unmanned aircraft, but for most of the twentieth century, drones were only really good enough for target practice. Meanwhile, hundreds of thousands of hobbyists flew model airplanes and helicopters. But the hobbyists flew for the sake of flying; for decades, there was very little their small aircraft could do. So the hobby remained a niche.

As is recounted in **Chapter 1** of this short book, all this changed quite swiftly in the last decade. The Global Positioning System (GPS) came online in 1995, suddenly making precise navigation possible anywhere on Earth. Early GPS units were not so accurate, so small, or so cheap. But this changed. So too with digital imaging sensors. Kodak made a working digital camera in 1975, but it was not until the early years of this century that such cameras became first accessible and then ubiquitous. Accelerometers were etched onto microchips in the late 1970s, but only in the 1990s did such microelectromechanical systems become common, when they were used to trigger automobile airbags. All of these components are crucial to the success of modern drones. (Which is not to say that any given drone cannot operate without a specific constituent technology. There are usually work-arounds.)

What, then, can drones do today? Equipped with sophisticated gimbals that allow cameras to freely rotate, they can get never-before-possible shots for Hollywood action movies. Pared down to the lightest possible weight, with cameras that communicate with small screens embedded in goggles worn by the pilot, they can zigzag through obstacles at speeds impossible for model-airplane hobbyists of decades past to have even aspired to. They are, like the personal computer, a multipurpose device. But though drones might commonly one day act as radio relays or couriers, at present they excel at one task: gathering images.

How drones gather images, and what people can do with the images they gather with drones, are the principal concerns of this book. In particular, we are concerned with images joined together into maps. Maps are among our most powerful social artifacts as humans. For most of history, it was impossible to create accurate maps. Then, for a while, it was very difficult, requiring both specialized knowledge and a great deal of resources. One of drones' many boons is to democratize the process of mapmaking. They are far cheaper than the mapmaking technologies they replace. Together with widely available satellite imagery, they are revolutionizing mapmaking. Though the knowledge required to operate drones is a barrier to entry, it is not an insurmountable one. This book is intended, in part, as a helping hand over that barrier for those interested in making maps with drones who do not know how to begin doing so.

Clear and secure rights to property—land, natural resources, and other goods and assets—are crucial to human prosperity. Most of the world's people lack such rights. That lack is in part a consequence of political and social breakdowns and is in part driven by informational deficits. Maps made by drones—and by unpowered aerial platforms such as kites and balloons—can chip away at these deficits.

Such maps have the capacity to help the weak defend themselves against would-be exploiters who, for instance, might take land that does not rightfully belong to them. But there is nothing to say a map made with a drone will inherently be of any good to anyone. **Chapter 2** of this book, by Mathew Lippincott and Shannon Dosemagen, discusses how one might think critically about the data-gathering process so that it might be of the greatest good to the greatest number. Their case for "people-centric mapping" is a strong one.

Chapter 3 of this book is a brief exploration of some issues in the regulation of drones. It is an odd quirk of modernity that it is safer to fly in a pressurized tube many miles above the Earth, at great speed, than it is to walk down a city street. The safety of air travel is one of the great regulatory successes of our time. And yet, aviation regulators are struggling to adapt to a new reality of a proliferation of small aircraft. This chapter discusses some pathways for harmonizing drone traffic with manned aviation. It also discusses some of the perils that drones bring with them. Along with other digital technologies that have large memories and fast brains, they have the capacity to chip away at solitude and privacy. This chapter discusses how a reassertion of property rights in the air can both protect privacy and allow for technological innovation.

Chapter 4 is the nub of this work. Though drones have made mapmaking much easier, it is far from a point-and-shoot endeavor. This chapter discusses the sorts of hardware and software that are necessary to make a map, and it explains the principles behind the process—principles that will remain even as hardware gets cheaper and software gets faster.

Chapter 5 narrates a number of examples of mapmaking in practice. It tells the story of Gregor MacLennan, who, together with Wapishana tribespeople, built drones and made maps of Guyana's rain forests and savannahs with the aims of thwarting illegal mining and negotiating just property boundaries. It discusses Walter Volkmann's efforts to update the Albanian cadastre, or record of property holdings, using a drone to accomplish in three hours what might have taken a month using traditional techniques.

Sometimes the maps that drones make come with great urgency, as in the aftermath of a natural disaster. In **Chapter 6**, Patrick Meier discusses his efforts to use drones as part of the response to Cyclone Pam in Vanuatu and the 2015 earthquakes in Nepal, among other calamities. In the chaotic aftermath of an extreme storm or an earthquake, systematic information is invaluable. This chapter discusses how best to go about obtaining such information and how to do so in collaboration with other humanitarian responders.

In the public domain, perhaps the richest experience with using drones to gather data in the last few years has been by scientists, in particular by those seeking to understand wildlife and ecosystems more broadly. Serge Wich, an ecologist who studies primates and tropical rain forests, and a drone pioneer himself, authoritatively surveys the extant scientific literature on these subjects in **Chapter 7**.

There is great hope that drones, with the new capabilities they provide, might help protect the most vulnerable among us when their human rights are jeopardized. **Chapter 8** analyzes the United Nations' use of drones in Haiti, the Democratic Republic of the Congo (DRC), Mali, and Chad, as it wrestles with the difficult task of protecting civilians in troubled and violent parts of the world. It also discusses monitoring efforts in Ukraine by the Organization for Security and Co-operation in Europe. This chapter then turns to nongovernmental organizations that aim to use drones to document human rights abuses and thus hold perpetrators to account, raise awareness, and hopefully reduce such instances in the future. This has not been done much yet; drones remain a new technology, and though they're powerful, the information they can gather is sometimes palliative at best.

This work concludes with two case studies. **Chapter 9** discusses the Peruvian Ministry of Culture's drone mapping program. It is a massive program—in the past two years, Aldo Watanave and his colleagues have mapped nearly 500 archaeological sites. The goal of this program is twofold: it is a scientific endeavor, and it is intended to establish clear legal boundaries around archaeological sites in order to prevent illegal encroachment by developers.

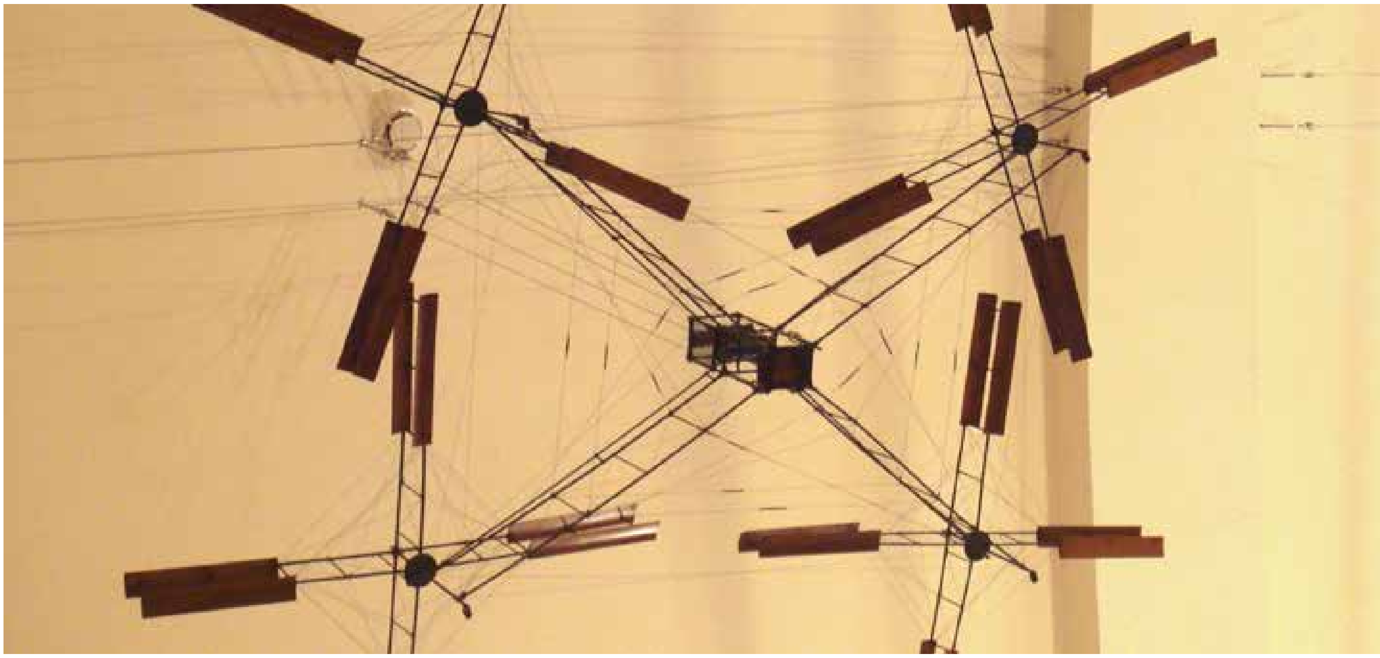
Chapter 10 is an examination of the UN's drone program in the DRC. The eastern part of that country, along the borders with Rwanda and Uganda, has been at war for nearly twenty years, and UN peacekeepers have been present there for the bulk of that time. The Falco drones being flown there are large and expensive, compared with many of the other drones discussed here. But they are far cheaper and more capable, with regards to observation, than the helicopters the UN had previously been using. This chapter points out one of the inherent limitations of drones. Information without the means to act upon it is still of value; however, that value is circumscribed.

On a final note, this book concludes with a look forward, trying to understand what is likely to change about drones as the technology continues to evolve, and what is not.

This primer is being published in conjunction with a website: drones.newamerica.org. That website contains regularly updated information about noteworthy drone flights, as well as a compilation of worldwide drone regulations. §

CHAPTER 1: WHAT DRONES CAN DO AND HOW THEY CAN DO IT

KONSTANTIN KAKAES



Photograph from PGHCOM via Wikimedia commons

The first quadcopter, built by Louis and Jacque Bréguet with Charles Richet, weighed over 1,100 pounds and got 5 feet off the ground.

On June 16, 1861, Thaddeus Lowe, a 28-year-old man from New Hampshire, hovered 500 feet over the White House, hanging in a tiny basket from a balloon of his own design. "This point of observation commands an area near fifty miles in diameter—the city with its girdle of encampments presents a superb scene," Lowe wrote in a telegram to Abraham Lincoln, who waited far below. This was the first electronic message to be sent from the air to the ground.[1] Aerial observation has a long history; Lowe was not its first practitioner. But the point he made remains true today; aerial views command a great deal, in both senses of the word. Lincoln would support Lowe in his struggles with the military bureaucracy, which was largely uninterested in his ballooning innovations. On the night of May 4, 1862, Lowe saw the Confederates attempt to secretly retreat from Yorktown, Va., under the cover of night: "The greatest activity prevailed, which was not visible except from the balloon," Lowe wrote.[2] Nevertheless, Lowe's balloon corps would soon be disbanded after General George McClellan, who had been a supporter of Lowe's, was forced out of his command following a massive retreat up the James River.

Lowe failed to fully realize his ambitions for aerial observation in part because of bureaucratic inertia, but also because of the technological limitations he faced. He could communicate with the ground only through a tethered cable; he could effectively observe only with his own eyes; he could fly only where the wind would take him. In the century and half since Lowe's flight over the White House, military needs have been the primary driver of innovation in aerial observation techniques. In the past decade, however, a number of technologies have evolved to the point where they are small, cheap, and light enough to enable a dramatic democratization of aerial observation. Crucially, small aircraft are now capable of flying themselves and gathering information with minimal human intervention—and without a person on board. These aircraft, which range widely in size, cost, and endurance, are known as drones, unmanned aerial vehicles (UAVs), unmanned aerial systems (UAS), remotely piloted aerial vehicles (RPAVs), and remotely piloted aircraft systems (RPAS). We will use these terms interchangeably, but mostly, we will call them drones.

There is no one element that makes a drone possible. Nor is there a clear dividing line between drones and manned aircraft. Automation has become increasingly important in manned aircraft. Drones require human intervention. Some planes are "optionally piloted." Nevertheless, drones constitute what W. Brian Arthur, in his book *The Nature of Technology*, called a new technological domain.[3] Domains, Arthur wrote:

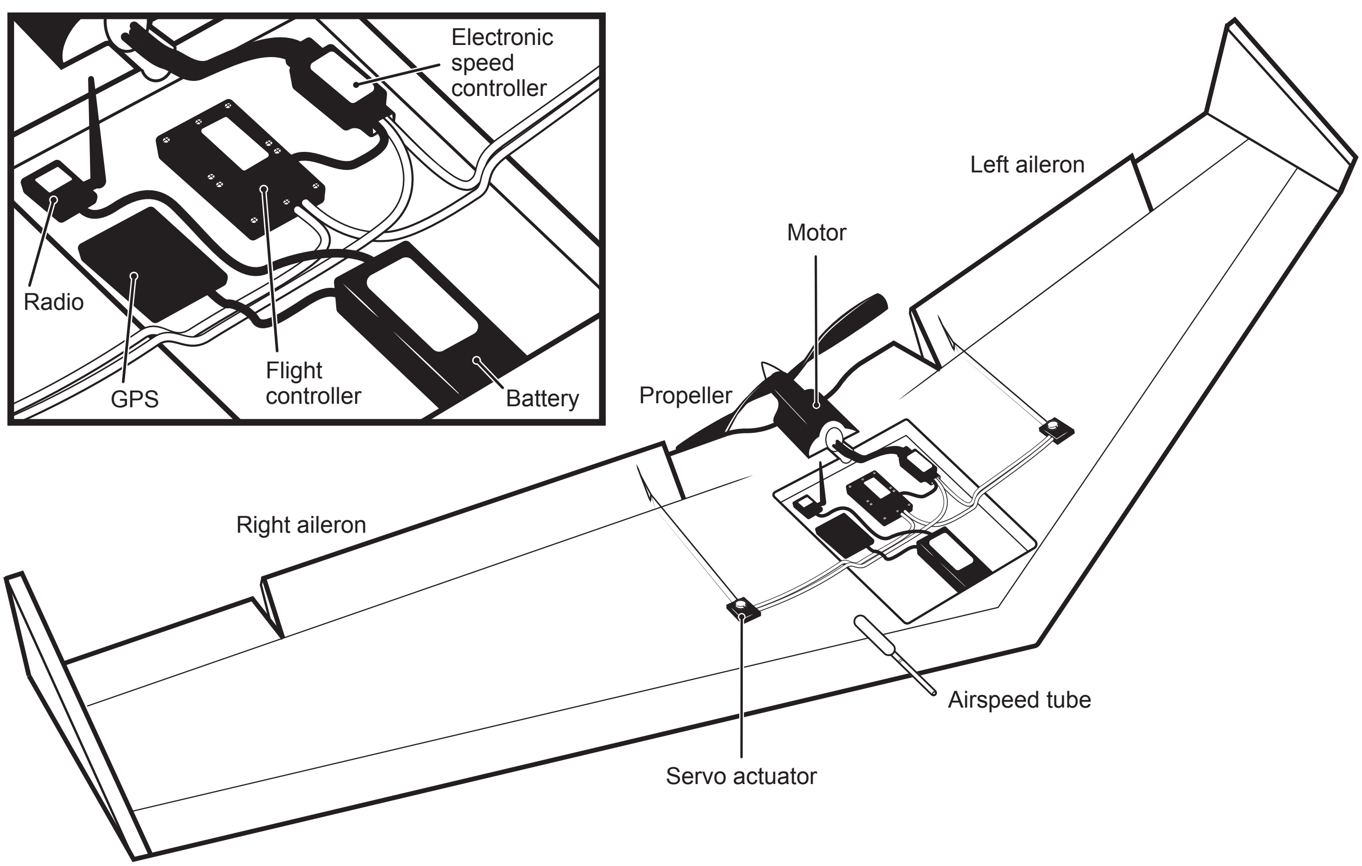
> are more than the sum of their individual technologies. They are coherent wholes, families of devices, methods, and practices, whose coming into being and development have a character that differs from that of individual technologies. They are not invented; they emerge, crystallizing around a set of phenomena or a novel enabling technology, and building organically from these. They develop not on a time scale measured in years, but on one measured in decades.

As a new technological domain emerges, Arthur explained, "different industries, businesses, and organizations encounter the new technology and reconfigure themselves. … A new version of the economy slowly comes into being."

This short book is about some of these reconfigurations insofar as they affect the nexus of humanitarian work and development, with particular attention to the role drones can play in enunciating, and thus protecting, property rights. It does not consider the use of drones for offensive military purposes, or for law enforcement or counterterrorism purposes. It also does not discuss purely commercial ventures such as the use of drones to film scenes in Hollywood or to inspect oil pipelines or bridges. These are all worthy subjects, but beyond the scope of the present work. These boundaries are not hard and fast; militaries and police forces are normally involved in disaster response, which is discussed in Chapter 6. The U.N. peacekeeping force in the Democratic Republic of the Congo, discussed in Chapter 10, is indisputably a military force, but one whose intervention is fundamentally motivated by the protection of civilians. This work also does not much discuss the use of drones for delivery of physical goods. This is potentially an important application, particularly in parts of the world lacking good surface transportation infrastructure. However, it is one whose technological maturity is somewhat farther off. This book focuses on examples of work using drones in the recent past—surveying land in Albania, Guyana, and Indonesia, or responding to disasters like the 2015 earthquakes in Nepal—and considers how similar work can be done in the immediate future using today's drone technology.

The reconfiguration that drones are catalyzing is an ongoing process. This primer presents some views about how it *ought* to take place, as well as concrete guidance about how to use a drone effectively.

Much of this primer is devoted to drones as mapmaking devices; it is perhaps the most important transformative use of drones today. Drones are very good at making maps far more cheaply than the techniques they are replacing. Drones now far outnumber manned aircraft—but it is the very small drones, like DJI's Phantom, that account for the vast majority of unmanned aircraft. These small drones are good at taking pictures, and computer image-processing



Delta-wing drones like the one depicted here are not aerodynamically stable, and could not fly if not for sophisticated electronics. The wing is usually made of foam. Some fixed-wing drones resemble traditional model aircraft, with a fuselage, wings, and a tail, and are more stable.

Illustration ©Valerie Altounian

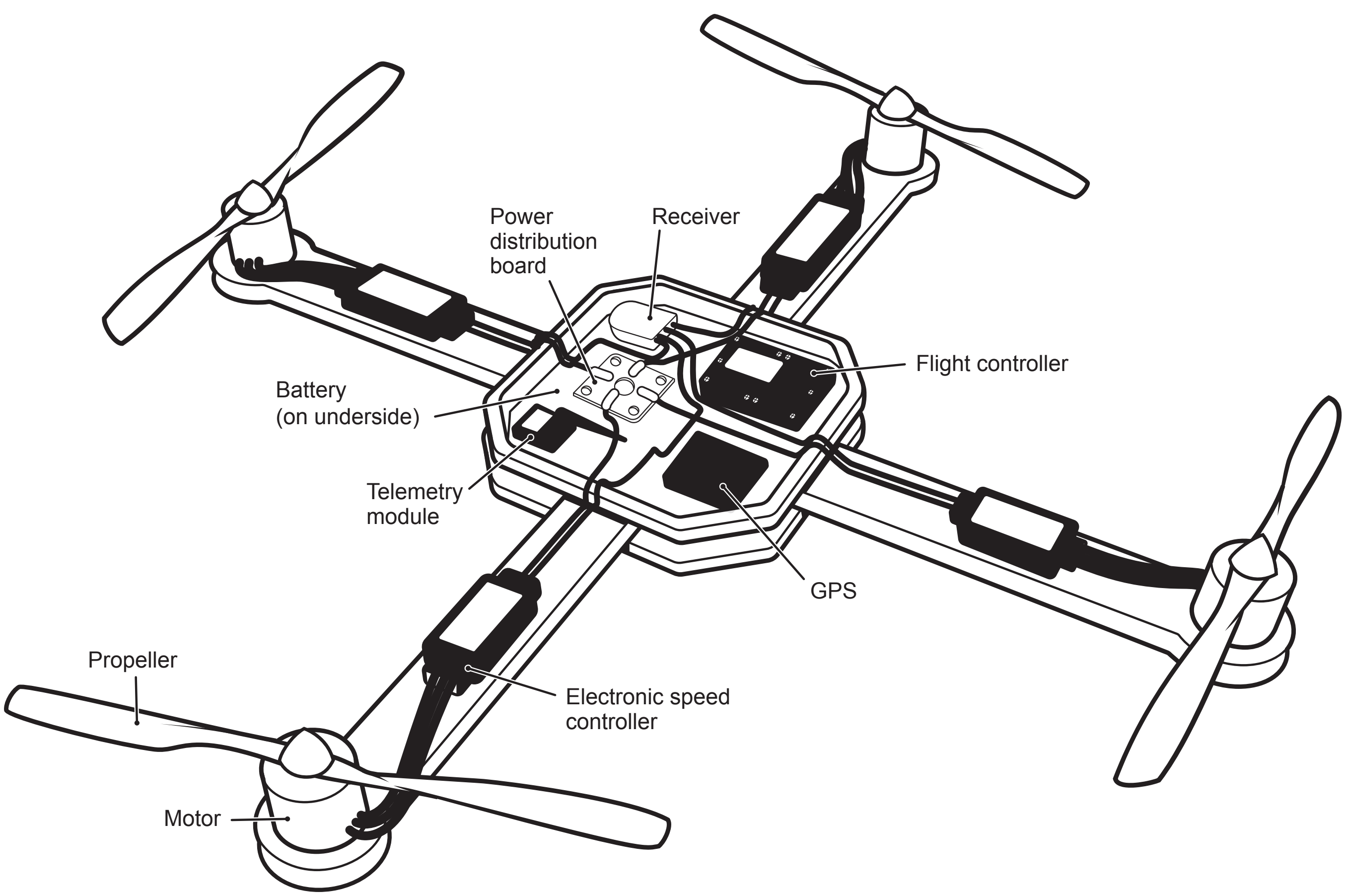
software is good at processing those pictures into maps. As Denis Wood puts it, "Maps are engines that convert social energy to social work. … Maps convert energy to work by linking things in space."[4]

A recurring theme in this book is that a drone—be it a small quadcopter that can fit comfortably on a cafeteria tray or a half-ton Selex Falco—is useful only insofar as it is part of a larger technological and social system. As Arthur explains, "A device seems to be a piece of hardware and not at all like a process. But this is just appearance."[5] This primer points to the importance of social processes surrounding drones; when sufficient thought is not given to those processes, even well-intentioned and well-resourced efforts can fail in their promise.

Nevertheless, it's worth examining the drones as devices to understand their limitations and possibilities. What are the technologies that make them possible and what are the limits of those technologies? Why do drones look the way they do? How do they, as devices, compete with other similar devices—most importantly, satellites—in doing the work they do?

Since the advent of powered flight at the beginning of the 20th century, inventors, from the Wright brothers themselves onward, have wrestled with the challenge of controlling an airplane without a person on board. In 1907, Louis and Jacques Bréguet, brothers from a family of clockmakers, built the first quadcopter, the Gyroplane No. 1, with the help of Charles Richet, who would receive the 1913 Nobel Prize in Physiology or Medicine. "The Bréguet-Richet quadrotor consisted of four long girders made of welded steel tubes and arranged in the form of a horizontal cross, looking somewhat like an assemblage of ladders. Each rotor consisted of four light, fabric-covered biplane type blades, giving a total of 32 separate lifting surfaces. The rotors were placed at each of the four corners of the cross."[6] As J. Gordon Leishman explains, "Diagonally opposite pairs of rotors rotated in opposite directions, thereby canceling torque reaction on the airframe." This was the first implementation of the same principle used in small quadcopters today. The Bréguet-Richet quadcopter weighed over 1,100 pounds; the pilot sat in the middle below a 40 horsepower engine. The quadcopter flew in August 1907. It got about 5 feet off the ground.

Gyroplane No. 1 was limited not by power, but by stability. Though in principle the opposite spin of the propellers would cancel out one another and allow the aircraft to rise straight up into the air, in practice small imbalances in the force generated by each propeller meant that for the aircraft to fly, it would have to be able to detect these imbalances and correct them. Devices for achieving stability were easier to implement in fixed-wing aircraft. In 1909, Elmer



Multirotor UAVs are laid out in a variety of different ways. This image displays one possible configuration.

MODEL P

No drone better represents the industry's turn toward inexpensive and accessible drones than DJI's line of Phantom UAVs. They are common first drones, but are capable enough to belie their toy-like appearance. As of 2015, DJI sells three series of the Phantom: the new 2015 Phantom 3 series, the Phantom 2 series first released in 2014, and the Phantom 1 series first released in early 2013. Models are differentiated within each series by their cameras and control systems.

As of this writing, unlike the Phantom 2 and Phantom 2 Vison+, the newly-released Phantom 3 does not yet have an established track record.* Furthermore, it has two serious drawbacks for mapping and fieldwork more generally. Neither its camera nor its gimbal can be removed or changed. Furthermore, it has no support for waypoint navigation.†

The Phantoms use proprietary lithium-polymer batteries to power their rotors, cameras, and gimbal systems. DJI claims the quadcopters can achieve a maximum flight time of 25 minutes; however, users report actual flight times of around 12 to 15 minutes. While this may sound paltry, it is adequate for mapping small areas and other photography needs, with copious use of expensive $149 spare batteries.

The Phantom 2 Vision+ is favored by hobby users and casual drone pilots for its plug-and-play functionality. It uses a camera of DJI's own design to shoot video and still photography. The camera, the angle of the camera, and some flight features, such as creating navigation waypoints and tracking battery life and altitude, can be controlled remotely with the DJI Vision app on Apple and Android mobile devices. Things get more complex but also considerably more customizable with the Phantom 2, which ships without a camera, waypoint navigation abilities, or a gimbal. If it is to be used to make maps, the owner must separately purchase a gimbal and a camera. A popular combination is the H3-3D gimbal and the GoPro Hero line of cameras. Some Phantom users doing mapping projects prefer to use small, lightweight point-and-shoot cameras instead, which prevent the bothersome "fish-eye" effect of both DJI's Phantom Vision+ and Vision cameras and the GoPro line. Some point-and-shoot cameras, such as the Canon S100, are also equipped with GPS-logging abilities, making it easier to georeference aerial maps.

Using a point-and-shoot camera with the Phantom 2 requires some technical ability, as the camera must either be controlled remotely or be programmed to take pictures at intervals, which is only possible with some camera models. Furthermore, off-the-shelf gimbals for the Phantom 2 that accommodate these point-and-shoot cameras are not available, so users have to hack together their own solutions, though ample advice on how to do this is available online.

Though the Phantom 2 cannot fly autonomously between waypoints out of the box, it can do so with the purchase of an additional DJI datalink system. The Phantoms are all reasonably rugged, although the plastic "arms" of the drone's body have been known to snap off after hard crashes. In a crash, the gimbal and the camera are much more likely to be seriously damaged than the drone itself. The Phantom 3 and Phantom Vision+ models are less durable in this respect, since the gimbals and cameras are integrated into the body. Phantoms are not waterproof.‡ Flight shouldn't be attempted in rain or heavy winds. The Phantom is reasonably portable with the propellers removed and can be comfortably and successfully transported in a large backpack. Many users purchase foam-lined hard cases to take the Phantom across international borders.

Sometimes Phantoms "fly away." The pilot loses control of the drone—an expensive and potentially dangerous mishap. While this may sound intimidating, the problem doesn't seem pervasive. DJI has corrected the firmware problems thought to be at the root of some recent crashes. Safety-minded pilots (and those with limited budgets for replacements) should ensure the Phantom 2's internal compass is always calibrated prior to flight, reducing the risk of an expensive miscommunication.

Matt Merrifield of the Nature Conservancy, a research and advocacy group, used the Phantom 2 Vision+ to count migratory bird populations on Staten Island, a protected area in California's Bay Delta. To Merrifield, the Phantom's utility goes beyond collecting data on migratory birds: aerial footage helps the public understand what the Nature Conservancy's work truly entails. "It becomes immediately apparent what we're doing—instead of a long document, it's an extremely powerful visualization tool. [The benefits are] hard to quantify."

While alternatives exist, the Phantom family of drones is the world's most widely used in the under-$1,000 category for good reason. Considering the Phantom's low price, ease of use, and integration with mobile devices, it's a hard system to beat in its class and a compelling choice for new drone pilots on a budget.

—Faine Greenwood

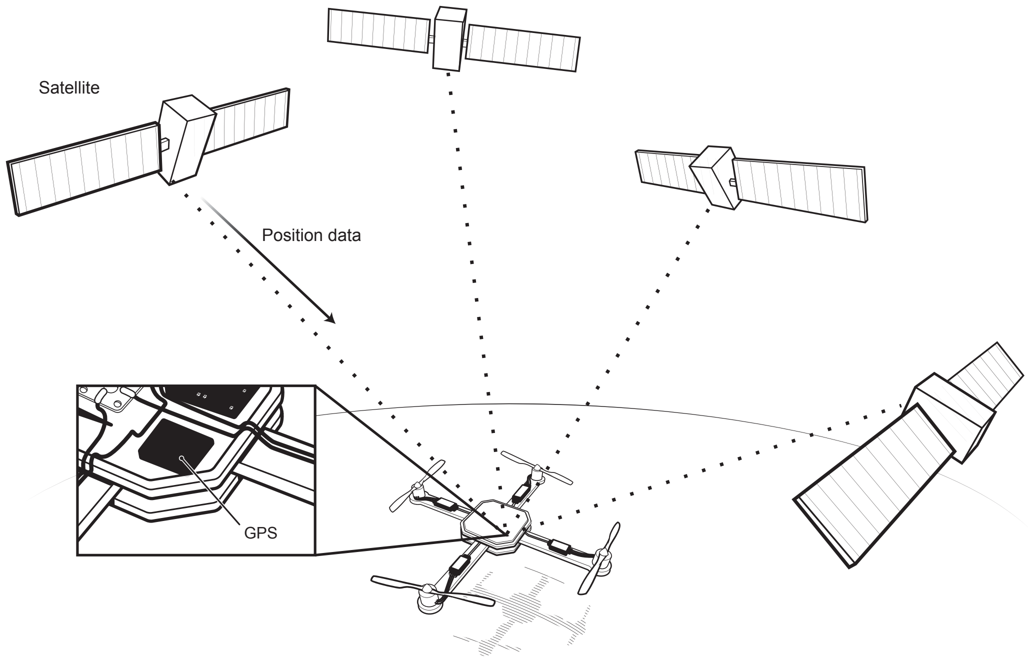
Vicki Burton via Wikimedia Commons

* The Phantom 2 Vision is not often used due to its diminished range of communication and its lower-quality gimbal, which often produces poorly stabilized footage.

† DJI is developing a software development kit (SDK) and is inviting others to create new features—but as of this writing, the waypoint problem hasn't been addressed.

‡ As a number of epic crash videos on YouTube demonstrate. See: http://makezine.com/magazine/drowned-drones-when-a-multicopter-hits-the-water/.

Sperry, an American inventor, began developing a gyroscope that would enable him to develop the Hewitt-Sperry Automatic Airplane, one of the first drones, a few years later. “Although Sperry’s intent was to improve the safety of flight by providing a pilot with vertigo or disorientation a mechanical sense of wings level, in doing so he also solved a key technical impediment to unmanned flight: stabilized flight in the absence of a pilot’s inputs. But his 30-lb gyrostabilizer, besides being excessively heavy, performed poorly when it encountered the three dimensions of flight.”[7] Before World War I ended, Sperry would develop a working unmanned aircraft, though interest in them would fade after the war.[8]



Global Positioning System (GPS) receivers work by inferring their position from timing data sent by a constellation of satellites. At least 4 signals are needed to do so.

Illustration ©Valerie Altounian

In place of Sperry’s 30-pound gyrostabilizers, today’s drones have autopilots that contain gyroscopes, accelerometers, magnetometers, and barometers, at a total weight of less than a tenth of a pound.[9] For a drone to fly successfully, these sensors must replicate what a pilot used to be able to do—what Wolfgang Langewiesche, in his book *Stick and Rudder*, described: “The pilot needs this sense of buoyancy also when climbing out of a tight airport. ... His life depends on his ability to sense ‘lift’ or the loss of it; most accidents happen only because the pilot’s sensing of his buoyancy failed him, and he stalled or spun.”[10] Though the difficulty of duplicating this pilot’s instinct in hardware and software is hidden from the end user who purchases a drone at Radio Shack, it is worth underlining the intricacy of the engineering challenges involved. Obviously, a crash of a drone does not imply loss of life; however, if drones were constantly crashing,* they would be unable to achieve what they set out to do.

Most drones use a variety of sensors to accomplish what is called “state estimation.” They use microelectromechanical (MEMS) chips to measure acceleration and rotation. Some carry lightweight onboard echolocation systems to measure the distance to the ground; some also carry barometers to measure air pressure. Some carry heat sensors called thermopiles, which can see the horizon. Some have magnetometers to measure the Earth’s magnetic field, and most contain GPS (global positioning system) sensors. GPS is needed because the MEMS sensors used in low-cost UAVs are not very accurate: “When operating as a standalone navigator, these sensors produce positioning errors on the order of several hundreds meter per minute.”[11] GPS, on the other hand, cannot update its position often enough and has its own fluctuations, so combining both sources of data is necessary. GPS relies on precisely measuring how long it takes radio signals to get from distant satellites to the GPS receiver. Because light travels so quickly, an error of just 10 billionths of a second in measuring that time of flight results in a positioning error of about 10 feet.[12] Maintaining stability without GPS input is an active area of research for both commercial drone manufacturers and academic aeronautical engineers. For instance, the DJI Inspire drone has some capability of doing this, but users report that it does not work as well as advertised.[13]

We will not go into great detail here on the functioning of autopilots. (The best succinct explanation can be found in “Fundamentals of Small Unmanned Aircraft Flight.”)[14] However, it is worth emphasizing how difficult a computational task is being accomplished under the hood , as it were, of drones. “The equations of motion for a [drone] are a fairly complicated set of 12 nonlinear, coupled, first-order, ordinary differential equations. ... Because of their complexity, designing controllers based on them is difficult,” as one textbook on drone design explains.[15] For a drone to fly, this sensor data must be reconciled; this is normally done using something called an extended Kalman filter, which takes into account not only sensor data, but also a physics-based model of how the given state of a drone affects its future states. (For instance, if a drone is moving forward at 60 miles per hour, or a mile per minute, in a minute it should have traveled one mile. So if your GPS measurement says it has only traveled only half a mile, your position measurement is likely off. The extended Kalman filter is a mathematical technique for reconciling inertial measurements of acceleration with GPS and other data sources. In practice, the time steps are

* Drones crash substantially more often than manned aircraft, but not so often as to make them impracticable, as was the case in, say, the 1920s.

on the order of fractions of a second, rather than a minute.) Techniques like this smooth out the volatility of sensor data.

In general, autopilots operate at two levels. A low-level loop maintains stability, while a higher-level autopilot, if engaged, follows a predetermined path from one GPS waypoint to another.[16] That higher-level autopilot may also include systems for detecting and avoiding obstacles; such systems are only now becoming available for consumer drones and are limited in functionality.[17]

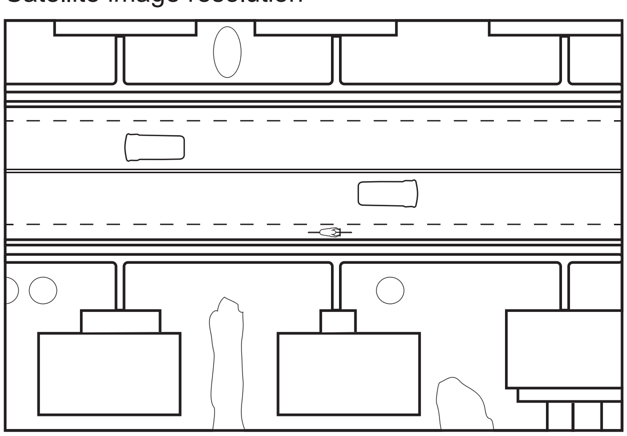
From a practical perspective, the would-be drone operator faces two major high-level choices: to use a fixed-wing or multi-rotor aircraft, and to buy a commercial system or build a "DIY" drone using commercial components. Open-source DIY solutions (of which the most popular are the ArduPlane fixed-wing http://plane.ardupilot.com/ and ArduCopter multi-rotor http://copter.ardupilot.com/) can be put together for a fraction of the cost of their commercial counterparts—from two to 10 times cheaper, depending on how exactly one counts costs and capabilities.

The choice between fixed-wing and multi-rotor UAVs is in part dictated by the exigencies of the market. The DJI Phantom is a low-cost, easy-to-use multi-rotor. No analogous fixed-wing model currently exists. Low-priced model airplanes like the Bixler require some skill to fly and assemble. It is surely only a matter of time until a drone company starts selling a Phantom-like fixed-wing. For the moment, though, novices seeking ease of use are pushed toward multi-rotors—not because they are necessarily more suited for a particular task, but because cheap and easy-to-use models are more widely available.

The trade-off between fixed-wing and multi-rotor drones is, obviously enough, one between endurance and maneuverability. There is also a trade-off in safety; fixed-wing drones can be very lightweight. A foam body or delta-wing craft can carry a small camera and still fly for over an hour. Fixed-wing drones are, all else being equal, safer than multi-rotors—if one loses power, it will likely glide to the ground instead of crashing abruptly. Fixed-wing drones are generally faster; though they can fly in small circles, they cannot hover, and cannot easily move vertically. Smaller fixed-wing drones can take off and land in fairly confined spaces, but not so confined as multi-rotors. Several hybrid models that have features of both types of drone are in development, though none as of yet has succeeded in the marketplace—the transition between vertical and horizontal flight is technically difficult.

The DJI Phantom, the world's most popular drone, has four propellers. This quadcopter design is quite common. It is, however, less efficient than a traditional helicopter design. "Single-rotor RC helicopters commonly have higher thrust-to-weight ratio, reduced drag, stiffer rotors, and more aggressive head mixing. As such, they can generally achieve greater agility."[18] The advantage of quadcopter (and other multi-rotor) drones is their mechanical simplicity. In a traditional helicopter, the angle that each blade has with the rotating hub at the center, called the pitch, must change in order to provide stability and maneuverability, a process called actuation. This complexity is, from a distance, hidden, but it makes helicopters difficult to build and maintain. On the other hand, in a quadcopter, each blade is set at a fixed angle, and stability and maneuverability come from varying the speed of each rotor individually, which is made possible by the sophisticated electronics in drones. In fact, adding rotors further reduces efficiency and therefore flight time. It does, however, make it possible to carry a heavier weight and allows for redundancy—the aircraft can keep flying even if one rotor goes out.

Octorotors like the DJI Spreading Wings S1000 tend to have limited endurance. The greater number of rotors (which are, like those in most quadcopters, not actuated)[19] provides a degree of redundancy in case one motor fails and allows the drone to carry more weight (up to 11 kilograms total takeoff weight,[20] of which nearly 7 kg can be payload). But because of the high energy demands of eight rotors, the S1000 can fly for only a maximum of 15 minutes, per DJI's



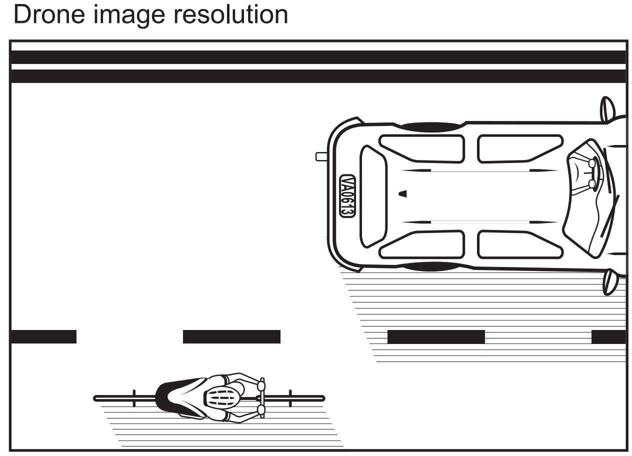


Illustration ©Valerie Altounian

Pictures taken by simple drones flying at typical altitudes show details as small as 1cm. The highest resolution commercially-available satellite imagery has 30cm resolution.

MAPPER'S DELIGHT

The black-and-yellow SenseFly eBee looks like an unremarkable flying-wing UAV, with a 38-inch wingspan and a body constructed from foam.* It is propelled by an electric pusher-propeller driven by a 160-watt brushless dc motor. The propeller is secured to the wing with a rubber band to allow it to bend with the wind. If the foam body breaks, which is quite possible, SenseFly will send another one.

It can afford to. The eBee costs $25,000.† This is not because of its airframe, but because of the software and hardware it comes with. The eBee weighs just under a kilogram and has a cruise speed of about 40 kilometers per hour. Its light weight makes it inherently safe and easy to travel with. However, the eBee is prone to being blown off course in heavy winds.

But its central appeal is that it flies itself. Most fixed-wing UAVs require the user to develop at least some piloting skill. However, the eBee has been developed as a fully autonomous system. To begin a mission, the user has simply to shake the eBee until the motor starts and then fling it into the air. The eBee will begin circling a previously set point to gain altitude and will then carry out its preprogrammed mission.

The eBee can even land itself with a reasonable degree of accuracy: it is able to detect how far it is from the ground when it comes in for a landing, and if users have defined a landing path ahead of time, it can make its way into narrow spaces. The eBee ships with proprietary software for both mission planning and post-flight image processing and photogrammetry. SenseFly's software can create a low-quality orthomosaic preview of aerial data that the eBee has just collected while still in the field. After processing the images for hours, users can also "fly through" 3-D point clouds the eBee generates.

The main downside of all this indisputable convenience? Price. The SenseFly eBee is expensive for a "foamie" fixed-wing mapping UAV. Technologically savvy researchers can build comparably capable systems for an order of magnitude less money.‡ Such models evade another issue with the eBee. It is a "black box" system, not amenable to being modified or tweaked. Nevertheless, the eBee's ease of use and reliability make its popularity easy to understand. —FAINE GREENWOOD

* "eBee senseFly," senseFly, https://www.sensefly.com/drones/ebee.html

† Baptiste Tripard, interview with the author, June 22, 2015.

‡ See, for instance, the Unicorn (http://unicornwings.stores.yahoo.net/) or Zagi (http://www.zagi.com/zagi-rc-electric-wings).

specifications.[21] By contrast, DJI says its smaller quadrotor Phantom 2 can fly for 25 minutes.[22]

These 300 grams, in the case of a Phantom, must be divvied up parsimoniously. Assuming one is using the drone as an image-gathering device, it must carry, aside from a camera, a gimbal that can both point and stabilize the camera. Mapping drones can get away with simpler gimbals, but if you want to surveil a particular location with a video camera, for instance, the gimbal must be able to compensate for the drone's motion. This adds weight and complexity.

If a mission requires a drone with a longer endurance or larger payload capacity, the cost rises very quickly. Low-cost drones, which can fly for roughly an hour in the case of fixed-wings or 20 minutes in the case of multi-rotors and carry a small camera, can be had for about $1,000. However, if one wants to implement persistent surveillance, say, in a conflict zone, costs rise very quickly. At some point, solar power might allow for low-cost, lightweight drones that can stay in the air for long periods and thus, though they travel slowly, survey large areas. Algorithms for autonomy are also likely to improve substantially in the coming decade, perhaps allowing for landing, refueling (or recharging), and takeoff to happen without human intervention. The capabilities of sensors (discussed in more detail in Chapter 4) will also improve, allowing a drone of comparable payload capacity to gather higher-quality data, or data of a different kind. For instance, both hyperspectral cameras, which can use detailed measurements of the wavelengths of reflected light to infer what kind of vegetation is present, and LIDAR (light detection and ranging) systems, which use lasers to measure distance, are growing cheaper and lighter. At present, the gap in capabilities between a small drone and a large one is profound. The importance of this gap will diminish with time, but for now it is substantial.

To take the comparison of cheap to expensive drones to its extreme, the most capable image-gathering drones are satellites, which are effectively very high-altitude drones. WorldView-3, a modern reconnaissance satellite operated by DigitalGlobe, cost $650 million to build and launch.[23] However, the cost comparison between drones and satellites is not so straightforward. A humanitarian customer can buy imagery, at 30-centimeter resolution, from DigitalGlobe for $250 to $300[24] for a 25 square kilometer image (ie one whose sides each measure 5 km). Whether this is cheaper or more expensive than using a drone obviously depends on how extensively a drone is used, and therefore amortized. Other relevant questions include cloud cover. In the tropics, cloud cover obscures about 40 percent of Landsat images, which capture large areas; the figure will be higher for higher-resolution DigitalGlobe images.[25] Additionally, cloud cover can introduce systemic errors: "Cloud cover can be very misleading because it might obscure only a very small (and thus presumably irrelevant) percentage of the total land area, but even this small amount of ambiguity can have large effects on the forest loss estimates."[26] Although small drones will never be able to cover as large an area as, say, Landsat can, they can be used in combination with satellite imagery to improve estimates of things like deforestation.

Additionally, as is discussed in Chapter 2, the fact that drone images can be made in collaboration with a local community, while satellite images cannot, is important. The higher resolution (1-2 cm instead of 30 cm) obtainable from drone imagery is not always technically necessary; however, it can make it far easier for non-specialists to interpret imagery, an important consideration as drone technology is democratized. As Josh Lyons, who works with both satellite and drone imagery at Human Rights Watch, says, "Drone imagery shows you a picture of a house and every single thing is far more readily identifiable to an untrained eye." This difference matters not only to untrained observers, but also to seasoned ones.

Of drone imagery Lyons gathered in Haiti, he says , "What was quite profound, what I realized as I started to process the imagery: I took this. This was my imagery. I haven't just bought it from some big American company. … What became immediately clear was the development capability. Everywhere kids would follow and watch; kids wanted to know about the battery and the camera." Though the price of satellite imagery is declining rapidly, Lyons points out that satellites will not ever have this social effect. The lower resolution of satellite imagery, though useful for many purposes, "systematically underestimated the damage" by a factor of almost two after the 2010 earthquake in Port-au-Prince, Lyons says. "UAV imagery," he says, "wouldn't have been perfect, but nothing ever will."

Additionally, he says, the real analytic benefit of drone imagery over satellite imagery "is not the spatial resolution. It's the temporal resolution"—that is, capturing timely images. There are, today, "five satellites taking images of the same area in Damascus at 8:45 in the morning." (This is a better time for commercial satellite imagery providers because clouds are statistically less likely.) However, because drones can be sent up at specific times more easily than satellites, they have the capacity to capture "smoking-gun evidence" of human rights violations, Lyons says. Such evidence might elude satellites that arrive too late to help determine the who and why of, say, a destroyed village, but can verify only that the village has been destroyed.

As drones become more common, another limiting factor in their utility may be sheer data overload. Digital memory is cheap, and it is easier to gather data than to analyze it. The temptation to indiscriminately gather data is a risky one, as discussed in Chapter 2. In some cases, it makes sense to gather more data than human intervention can effectively analyze, and to use computer vision algorithms to parse it, as discussed in Chapter 7.

It is a mistake to think of government regulation as a force from the outside, hampering the capabilities of a technology such as drones. Drones—like manned aircraft and cars—are part of a network. The best car is of little use without good roads; air traffic control systems enable airplanes to fly without crashing into one another. Vast increases in the number of drones will require both new, smart regulation and new technological systems for managing drones' interactions with one another. Not all of the privacy quandaries that drones give rise to can be addressed by regulation, but many can. More on these issues is found in Chapter 3.

Drones will, in certain respects, be a transformative technology. It is difficult to imagine a future for aerial surveying by manned aircraft, for instance. In other respects, drones will be a useful tool on the margins. This is a consequence both of their evolving technical capabilities and of political decisions about how they ought to be employed. As Arthur wrote, "We should not accept technology that deadens us; nor should we always equate what is possible with what is desirable."[27] §

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CHAPTER 2: THE POLITICAL GEOGRAPHY OF AERIAL IMAGING

MATHEW LIPPINCOTT AND SHANNON DOSEMAGEN

NASA

How do we use drones to get good data for good purposes? Packed into this question are judgments about what good data is, how it can be controlled as it enters a networked world with a long digital memory, what good purposes are, and who exactly "we" are. It is a question without easy answers, but it is at the root of the ethics of drones as information-gathering devices.

The answer we have to offer is a simple one with no easy implementations: Data should be collected by, or in collaboration with, the people being observed, for questions they have a stake in defining, and for decision-making processes controlled by the affected people. At every stage from study design to rule-making, public participation and accessible data collection methods, when implemented well, increase the quality of collected data, the nuances of decision-making, and the legitimacy of resulting rules. As a 2008 study of environmental data-gathering by the U.S. National Academy of Sciences found, public participation is highly correlated with quality data, accurate hypothesis formation, and decision legitimacy.[1]

Drones are potent symbols of automation, surveillance, and secrecy, a tangible physical target amid a rush of networked sharing, snooping, and mass data storage. Emerging from collected advances in low-power computing, cameras, positioning, data transmission, sensors, and batteries, drones bring a distinct economy and scale to capturing images and information. It is tempting to take the novelty of drones as epochal given the breadth of technical mastery expressed by these nimble automated aircraft, but the capabilities united in drones, and the dilemmas they raise, are present in a variety of existing and emerging technologies. The symbolism of drones makes them convenient targets in debates about surveillance, citizenship, and technology. But these debates are not really about drones. They are debates over the dynamics of power and representation in science, surveillance, and mapmaking—debates with a long history.

The questions of "Who gets to make and view official pictures of the world?" and "Who and what get included in those pictures?" have remained stubbornly immune to purely technical fixes. Technologists have repeatedly

This picture taken by NASA's Terra satellite shows the Deepwater Horizon oil spill. Sunlight can be seen reflecting off the oil slick on the surface. Public Lab mapped the spill from lower altitudes using kites and balloons.

enthused that more precise data could put an end to bias in mapmaking, but when politics are pushed aside, innovations such as digital geographic information systems (GIS) have reproduced existing biases.[2] In public policy, maps detail both existing knowledge and future plans.

In April 2010, an oil rig in the Gulf of Mexico, the Deepwater Horizon, exploded and sank. Eleven people were killed and oil gushed into the gulf for months. The core tenet of Public Lab (then called Grassroots Mapping)—the organization we cofounded to response to the oil disaster—is that everyone has the right to capture their own geographic data to provide context for their situation, and should be able to control both the data and the process of data collection. The disaster gave Grassroots Mapping participants the opportunity to test these initial assumptions when Gulf Coast residents took to boats and beaches using simple point-and-shoot cameras and a stabilizing rig made from the top of a two-liter soda bottle, lofted to 1,000-2,000 feet on tethered balloons and kites. Mappers collectively captured over 100,000 images of 100-plus miles of coastline, documenting the movement of oil across the gulf between April 2010 and July 2010.

The initial goal—to create an archive of images of the disaster that would help people tell their stories—took on new urgency when the Federal Aviation Administration banned unapproved air traffic from flying under 3,000 feet above the gulf.* Images couldn't be captured from airplanes (or, for that matter, drones) because of the flight restrictions. So we took pictures from cameras attached to balloons and kites, which were tethered to the ground and light enough to evade the FAA's limits. This became both a technical and a social means of critiquing corporate and government power. Public Lab aerial mapping tools now include hardware kits including kites, balloons, and poles for aerial photography, as well as browser-based software (MapKnitter.org) for image collection, collation, editing, analysis, annotation, and export to standard geographic formats. The Public Lab mapping program supports communities in creating their own narratives and shaping civic discourse around rural and urban land access, environmental destruction, and contested populated spaces.

SURVEILLANCE AND DATA-SHARING

"In the pre-computer age, the greatest protections of privacy were neither constitutional nor statutory, but practical. Traditional surveillance for any extended period of time was difficult and costly and therefore rarely undertaken. "

—Supreme Court Justice Samuel Alito in *United States v. Jones* (2012)[3]

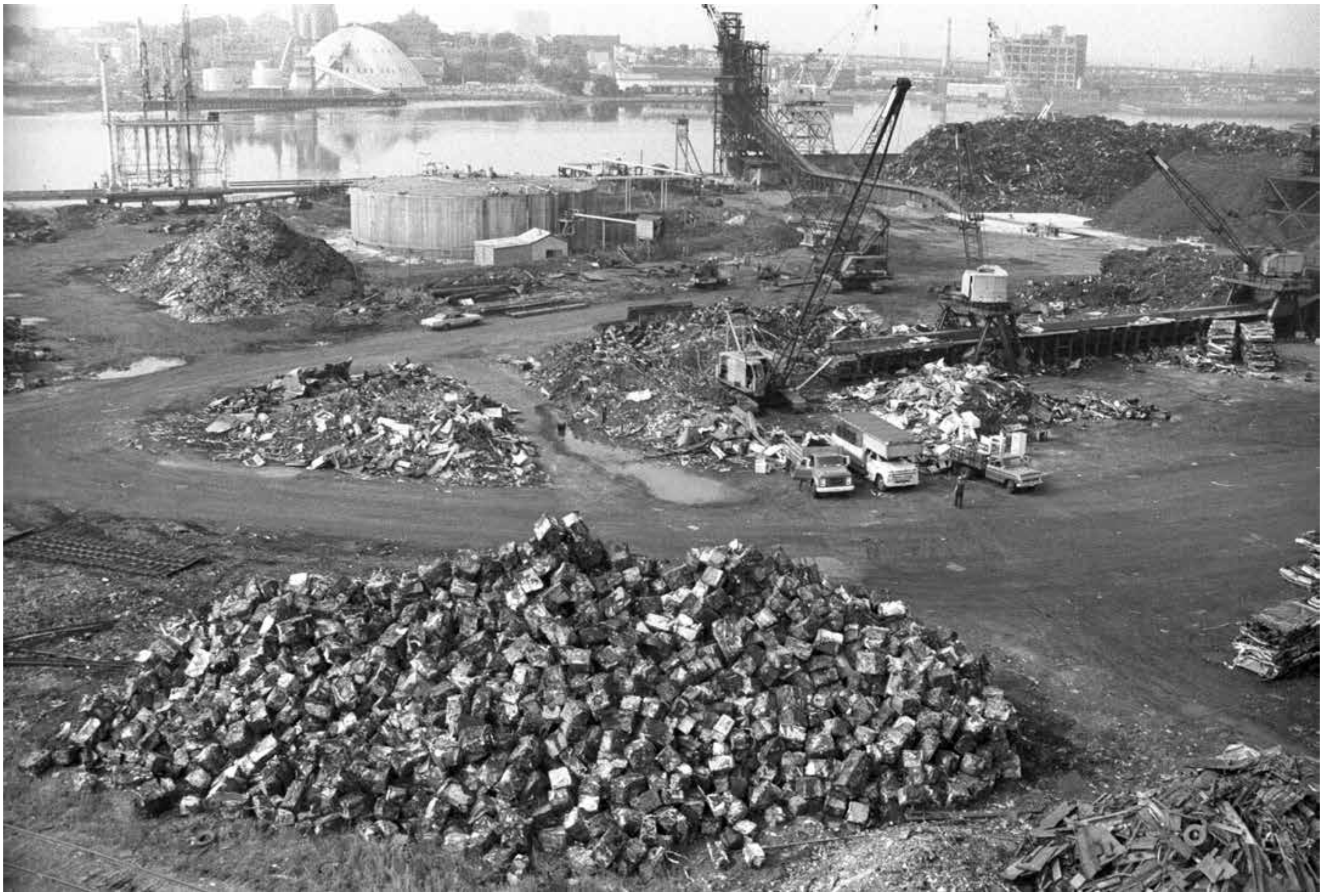
In 2010, a neighborhood group approached the Conservation Law Foundation (CLF), a Boston-based policy and legal nonprofit, about a scrap metal facility on the Mystic River. Observable rain water runoff demonstrated that the facility had never built a stormwater system†, as required by law. A quick search of Environmental Protection Agency (EPA) records revealed that the facility had never applied for or received a permit. It was flying under the EPA's enforcement radar, and so were four of its neighbors. Since then, CLF's environmental lawyers have initiated 45 noncompliance cases by looking for industrial facilities along waterfronts in Google Street View, then searching the EPA's stormwater permit database for the facility's address. Most complaints are resolved through negotiated settlements, in which the facility owners or operators agree to fund what are formally known as Supplemental Environmental Projects for river restoration, public education, and water quality monitoring that can catch other water quality criminals.[4] Together, CLF and a coalition of partners are creating a steady stream of revenue for restoration, education, and engagement in the environmental health of one of America's earliest industrial waterways.

Aerial and street-level geotagged imagery on the Web is a boon to both environmental lawyers and the small teams of regulators tasked by states with enforcing the Clean Water Act. Flyovers and street patrols through industrial and residential districts can be conducted rapidly and virtually, looking for clues to where the runoff in rivers is coming from. When combined with searchable public permitting data, the 1972 Clean Water Act's stormwater regulations are now more enforceable in practice than they have ever been.[5] With roughly half of commercial facilities violating the Clean Water Act every year and few receiving enforcement actions, state and federal regulators have little time for improving compliance, especially for unidentified facilities' self-report permits.[6] Lawyers are able to intercede in enforcement, bringing with them 40 years of Clean Water Act case law and returning a portion of the fines to themselves as well as to Supplemental Environmental Projects funds controlled by the local community.

Automated surveys like Google Street View make it so much easier for private parties to search for building code and environmental violations that they may encourage a shift away from government-provided safety and environmental health services. Environmental health and safety may improve or it may be degraded when public services like permit enforcement are left to private parties. This depends on the accessibility of data collection, accuracy of the data, and accessibility of the decision-making process, as well as the perceived legitimacy of the resulting decision. These factors are interrelated; if a decision-making process is not perceived as open and responsive to affected parties, it will be perceived as having less legitimacy.[7] If a decision is not considered legitimate, people are likely to ignore or evade it. If data can be collected only by a limited group or during limited times, data collection can be gamed to momentarily hide noncompliance.

* The flight restriction was put in place in order to coordinate air traffic involved in recovery operations, but had the effect of making it difficult for independent groups to gather aerial data about the oil spill.

† These are systems that either clean rainwater on site or send it to a treatment plant.



Spencer Grant/Getty Images

Compressed autos at Mystic River scrap yard, Everett, Massachusetts, 1974. The Clean Water Act took effect in 1972.

When government services are conceived only as arbitrations, parties must represent themselves authoritatively to government. Depending on the costs of representation, doing so may create power imbalances between those who can and those who cannot afford to represent themselves, either with lawyers or with data. Courts in the United States are an especially inaccessible decision-making framework. Only one in five low-income people are able to get legal services when seeking them.[8]

But businesses are not necessarily the villains in this situation. Legal threats are stressful and often expensive, even when threatened polluters are acting in good faith to clean up their act. Noncompliant small businesses on the Mystic River that had been operational since before the Clean Water Act may never have been alerted to their obligations under the law. Their absence from the EPA database reflects the EPA's lack of knowledge, but may also reflect the businesses' ignorance of the EPA as well. Businesses bear the direct costs of installed equipment, staff time, and facility downtime, indirect costs to their professional reputation from delayed operations or being seen as a polluter, and transactional costs of paying for legal assistance or court fees. Indirect and transactional costs are hidden punishments that can accrue regardless of guilt or readiness to comply.

Fear of surveillance contains fear over the stress, cost, and hidden punishment of explaining oneself in legal language. Is someone watching secretly from a distance, building a compromising narrative branding one a criminal for violating rules that aren't known or even readable? Can a narrow, legalistic charge represent the complexity of one's interactions with a landscape ranging from industry to stewardship, recreation, and consumption?

CLF proactively works to fit itself into a community-centered watershed management strategy. CLF and its partners run public education and outreach campaigns and begin any enforcement activity with a warning rather than a court filing.[9] Identifying and working with businesses operating in good faith is a tenet of community-based restoration efforts. By using courts as a last resort and participating in public processes where citizens can express the complexity of their relationships to the landscape, CLF and its partners are increasing participation in environmental decision-making and establishing the legitimacy of restoration and enforcement decisions.

Drone-based surveys will expose rule-breaking, just as Google Street View does. The acceptability of conducting surveys and the accuracy of those surveys will depend heavily on how rule-breakers are treated. Will drone surveys encourage stealthier violations of the rules, or a public evaluation of rules and community goals? Will homeowners camouflage their unpermitted toolsheds, or have a conversation about the nature of toolshed permitting? Hostility toward data collection and falsification of data are directly related to the accessibility of the decision-making process in which data will be used. The more distant the process, the more likely an attempt at measurement will become a target to be gamed for personal advantage.

One response to people who cheat surveys is to do more surveys. Some spaces are becoming subject to near-total surveillance to catch evasions and rule-breaking, a trend that drones' economy encourages. If increased surveillance allows more enforcement, then total surveillance raises the specter of "perfect enforcement," a theoretical state in which all the rules are enforceable all the time.[10] How perfect would perfect enforcement be? Currently, surveillance systems and police are deployed preferentially among historically disadvantaged groups and the poor. Whoever is watched for criminality is who will be caught for crimes and labeled criminal.[11] Automation and mass data collection may create more opportunities for discretionary enforcement than they solve, as every new camera angle adds another incomplete frame of view.

Surveillance can produce detailed data that rules cannot handle. Already, traffic cameras and automated toll-taking on some roads mean that every car's speed is known. If someone breaks the speed limit for 20 minutes, are they fined the same as someone who breaks it for two minutes? What if someone breaks the speed limit for a total of 20 minutes, but in 10 two-minute periods? There is no legal guidance as of yet, leaving jurisdictions to make their own discretionary judgments, few of which are published.[12] Existing surveillance technologies are leading to secret rule-making around public spaces.

Data does not stand alone. It is always worked into narratives shaped by authors' choices, ethics, and biases, in service of a point. Protecting data and setting privacy standards are about giving the subjects of a data collection program a say in the narratives that others can build about them. Aerial images are most powerful when associated with other information. Drone surveyors need to consider not just privacy as it relates to their own data, but also how it relates to cross-referenceable data. For decades, computerized, cross-referenced databases have been raising data privacy questions around how narratives are built. In 1973, the U.S. Department of Health, Education and Welfare issued a statement of remarkable clarity on the collection and use of personal data:

The Code of Fair Information Practices is based on five principles:

- There must be no personal data record-keeping systems whose very existence is secret.
- There must be a way for an individual to find out what information about him is in a record and how it is used.
- There must be a way for an individual to prevent information about him that was obtained for one purpose from being used or made available for other purposes without his consent.
- There must be a way for an individual to correct or amend a record of identifiable information about him.
- Any organization creating, maintaining, using, or disseminating records of identifiable personal data must assure the reliability of the data for their intended use and must take precautions to prevent misuses of the data.

—U.S. Department of Health, Education and Welfare, Secretary's Advisory Committee on Automated Personal Data Systems. Records, Computers, and the Rights of Citizens, viii (1973).[13]

These are principles that should be followed today. However, since the 1970s, government policy and corporate practice have moved in the opposite direction, despite little change in citizens' desire for privacy.[14] Personal information is routinely collected, stored, and sold in secret by both public and private entities, undermining trust. We suggest the following guidelines for collecting and using data:

- If you don't need the data, don't collect it. If you're building a set of data via aerial mapping techniques, know why you're collecting the information. Don't collect information that won't be used for a specific purpose.
- Collect data in a way that allows for participation: Work with people who are affected by the data you'll be collecting. In doing so, create relationships centered on trust and common goals.
- Avoid gathering or storing data about others without their knowledge. Surreptitious data-gathering may be necessary, for instance, in documenting human rights violations. If it is possible to obtained informed consent, do so.
- Store data contextually: If the information is necessary in a certain context but presents risks in others, create a system of storage that limits future context changes through record sunset provisions or other means.
- Support ownership and control of the data by the people it is about. Information will be richer in context, scope, and applicability when people feel it is honestly for them.

Right now we appear to be in a civic arms race to collect data and expose other people's secrets, pitting state and corporate surveillance against activist counter-surveillance. In the realm of video, narratives about policing are built around footage of police. Police cameras, dash cameras, and security cameras compete with cop-watching mobile phones and public data requests to get footage and move opinion. Counter-surveillance extends beyond visible light into invisible frequencies, with activists deploying midwave infrared video cameras to detect leaks at gas facilities and new software-defined radios to track secret FBI planes.[15] This surveillance arms race is indicative of low trust in official decision-making and the expanding use of secretive and adversarial tactics by government and corporate actors. Drones are rapidly being deployed on all sides in this arms race, and adversarial fear-based tactics appear to be driving debates about the place of drones in civil society.

In environmental monitoring, planning, and policy, adversarial relationships are widespread but government policy has been shifting toward open data and participatory processes. The U.S. Geological Survey (USGS), a scientific agency that is part of the Department of the Interior, combines imagery from private providers and the Department of Agriculture, and has worked to become a standards-based storehouse of map data rather than the primary surveyor.[16] OpenStreetMap, an open-source mapping initiative built on user contributions like Wikipedia, has attracted many municipalities seeking the advantages of pooled efforts and open licensing for their map data. The EPA has also warmed to civic science and low-cost monitoring tools with programs such as its Air Sensor Toolbox, a guide to air monitoring for community groups looking to gather their own data.[17]

Increasingly, mappers and researchers find themselves creating data in the official public record, raising questions about the public duties of volunteers and the accuracy of public data. The participatory, open-source geographic information system (GIS) response is circular but functional, as stated by Eric Wolf of the USGS. Wolf posits a feedback loop, where if data is good enough for people to use, then it will be used frequently enough to maintain and improve its quality.[18] Repeated use of geographic data in a real-world context lets people check its accuracy. Users who rely on the data will keep it accurate enough for their own use, as long as there are participatory avenues for improving the information. This open, process-oriented, and civic-minded approach to data collection offers a route out of the surveillance arms race.

MAPS AND LEGAL ACCESS

In the 1820s in what is now New Zealand, a Maori band under Nuku-pewapewa captured Maunga-rake *pa*[*] in a daring aerial night raid that opened the fortifications from inside. Nuku-pewapewa's warriors lifted a man quietly off a cliff and into the *pa* on a *raupo manu*, a bird kite woven out of rushes.[19] *Raupo manu* were kites that could fly without tails, the precursors to airplanes not yet known in the Western world.[20] Maori and other Polynesian peoples had practical kites for meteorology, fishing, and bird-scaring. However advanced their kite technology, Maori were unprepared for a defining colonial technology: the court system. The Native Land Court was created in the 1865 Native Lands Act. As the law's preamble states, the court was designed to "encourage the extinction of [Maori] proprietary customs."[21] The colonists' bureaucratic technology mixed accurate cadastral[22] mapping with arbitrary and litigious land titling to build a framework for acquiring Maori land.

Maori land tenure was based on nonexclusive use by individuals under nested power structures of *iwi* (overarching tribes), *hapu* (sub-tribes), and *whanau* (extended families). The Native Land Court assigned exclusive co-owned titles to no more than 10 individuals. Properties were subdivided and passed to heirs, increasing the difficulty of making land-use decisions and connecting individuals to a host of small fragmented parcels. Absenteeism and the difficulty of coordinating heirs in land-use decisions encouraged many Maori to bring their titles to the Native Land Court to convert to freehold titles. Between 1860 and 1890, 8 million acres were sold.[23] Many traditional land-management schemes ceased, and raupo manu disappeared from the skies, their capabilities later reinvented by and attributed to Westerners. Nonsensical land fragmentation still haunts contemporary Maori in areas where customary titles were retained.[24]

To implement a mapping project equitably, one must understand the historical reproduction of bias through mapmaking, surveying, and titling. People-centric mapping has emerged from a recognition that new technologies in mapmaking have reproduced old biases, and their prescriptions are coherent only when viewed through a historical lens. Modern geography has its roots in state projects of land formalization that overwhelmingly favored powerful interests over marginalized peoples. The systematization of bias through maps is most acutely visible in land formalization. Land formalization is best defined as "the recognition and inscription by the state of rights and conditions of access within specific boundaries."[25] We will use "informal land tenure" to define customary land use practices that are not recognized by or registered with the state, acknowledging that these practices are quite formalized within their geographic scope and culture. While the systems of rights and conditions attached to formalized land have varied immensely between different states and regimes, these systems have been implemented under a shared desire to make land calculable and governable from a distance.[26] In contemporary practice this usually means registering ownership through single-holder land titles and maps in order to integrate parcels into a market and quantify their taxable resources.[27]

Moving from informal to formal land tenure involves translating varied local practices into standardized forms. Exploiting this process to usurp land has been the rule rather than the exception. Local populations have often been treated as mutable features of a remotely managed landscape, setting the stage for exploitation and degradation. If, rather, surveyed populations are actively engaged as participants, the transition to formal tenure can be an improvement over the status quo. And change is needed. Developing nations have cadastral surveys for less than 30 percent of their domains.[28] Aerial imaging and automated computer vision assessments of factors such as population and building density are gaining popularity as methods for counting and locating informal settlements.[29]

A LIGHTNING HISTORY OF LAND FORMALIZATION

Pre-modern and early modern states relied on import duties, conscripted labor, and production quotas for revenue. Most modern and contemporary states prefer to quantify land and resources in order to regularize taxation and revenues. Land formalization is therefore a crucial means of asserting the rule of law and making taxation and

* A "pa" is a fortified village or hilltop fort.

the provision of state services transparent and legible* to citizens, especially following displacement by natural or human-made disasters. However, land formalization has served a dual role of describing space and remaking space into bureaucratically legible, mappable forms, a process eloquently described by James C. Scott in his book *Seeing Like a State* (1998). Land formalization programs are almost universally something more than registering existing owners' parcels, because informal land tenure is rarely defined by contiguous parcels, each with a single owner. Different resources may each be divided among different owners in non-contiguous and often overlapping plots. For instance, harvestable foods in a forests' understory may be divided in a different manner than those in the canopy, while firewood collection follows yet another pattern. Land-use rights may vary from season to season, especially where the territories of nomadic pastoralists overlap settled agriculturalists.[30] Rights may be transferable to others or not, and may be gender- or age-dependent. Resources may be held by households, individuals, or communities who trade or redistribute resource plots. Systems of informal land tenure may be equitable or discriminatory, egalitarian or hierarchical, but they have never been consistent.

Informal land tenure is usually very hard to draw on maps, and paper-based cartography is certainly inadequate for the task. The difficulty of recording and tracking informal land tenure for outsiders at a distance has led states to prefer simple schemes that fit their bureaucratic capabilities. Land boundaries and map scales are chosen for their bureaucratic legibility. States prefer simple forms of land management, especially contiguous parcels each assigned to a single owner with no seasonal variation. For those who have grown up under systems of single-holder land titles, informal land-use patterns may seem complex and illegible. Illegibility is often conflated with disorder, in both historical and contemporary land formalization. Land formalization and its disastrous consequences for many residents has been extensively documented in 18th to 20th century histories of Western, colonial, communist, post-colonial, and post-communist states. Formalization and the end of traditional land use may not only displace people and reduce agricultural productivity, but also increase state revenues through legibility, as it did in Tsarist Russia.[31] The interests of mappers and the mapped have rarely aligned.

WHY WE MAP

Despite the power dynamics that cartography has inherited, all sorts of people find making pictures of our world and linking them to locations on Earth attractive. Visually understanding our place in the world provides us with a sense of belonging. Maps communicate. They are a limited picture, cropped and simplified, claiming: "This is here."[32] Regardless of whom the map favors, all viewers are treated to an omniscient view. This omniscient view is seductively explanatory, regardless of whose claims the map validates.

Aerial and satellite photographs, stretched and processed into photo maps, have given an extra edge of realism to maps' perspective. At first restricted to large institutional and state actors, photo maps present an authoritative and naturalistic aesthetic, even though they are the result of heavy manipulation and combinations of sources whose origins are often hard to trace.[33] With the advent of consumer digital photography, decent aerial photo maps can be captured from technologies ranging from kites to the passenger seat of a commercial airliner. Access to photo mapping is broadening, with unknown effects on the authoritative aesthetic of aerial views.

When access to mapping requires privilege, the privileged alone paint authoritative-looking pictures about land use and tenure. When privilege is enshrined in systemic bias, mapping programs can formalize people's marginalization. Mapping programs can neglect to record existing land use accurately, effectively erasing people's customary tenure. People being mapped often do not have a voice in selecting which categories and systems are included in the map, or further engagement with official policy and geography.

The result is to inscribe the map's bureaucratic fragmentation onto the landscape. The map does not merely describe the world, but can catalyze the displacement of people and degradation of social structures as the world is reshaped to the map.

PEOPLE-CENTRIC MAPPING

Putting people at the center of a mapping program offers opportunities to unite inhabitants around their landscape and reclaim health and welfare as land-management virtues. A people-centric mapping program actively works to limit the privileges needed to engage in mapping, so that the people whose spaces are mapped can:

- Archive and review changing landscapes and uses
- Control the taxonomy of description
- Own and use the formats of presentation
- Access the prevailing discourse on geography and policy
- Open space for dialogue with all stakeholders

Changes in land-use norms and rules are usually justified with reference to maps. The above five points are key criteria for evaluating a mapping program or technology to examine whether it is actively countering systemic marginalization, accidentally reproducing injustice, or deliberately ignoring affected people.

The Public Lab New York City chapter has successfully engaged in a people-centric mapping program. Since 2011, community organizers and organizations around the EPA's Gowanus Canal Superfund site have used aerial mapping with balloons and kites to document and manage the urban ecosystem, contribute community-collected imagery to assist in the EPA Superfund plan, and act as advocates for

* Which is to say it is understandable through documentation.

the community and people in the watershed's reach. Using a people-centric approach to the aerial mapping of the canal has allowed the community to own and manage the imagery it has collected and provide a means for stakeholders to discuss the management and cleanup of the canal.

Aerial imagery is especially compelling when combined with direct observation from people canoeing the canal. Activists from the Gowanus Low Altitude Mapping (GLAM) project have been able to confirm their on-the-ground hunches about runoff and hidden drains with aerial images, adding to the Superfund cleanup map—and increasing the Superfund site by a city block. It is much easier to make a convincing case when the hands-on experience of community groups is mixed with clear images. Being able to use images in advocacy encourages GLAM and the Gowanus Conservancy to continue flying in their neighborhood, but they also do it because it's fun and generates local attention.

Recognizing residents as experts on their land and creating a fun space for them to annotate the best possible maps is a feature of Participatory 3D Modeling (P3DM), a PGIS/PPGIS (Public Participatory Geographic Information Systems) method in which room-filling 3D topographic maps are set up in public places.[34] P3DM was developed in the late 1980s through the Thailand Upland Social Forestry Project's Participatory Land Use Planning program with anthropologist Uraivan Tan-Kim-Yong. Its use in land planning has since expanded in Thailand and entered regular use in the Philippines and elsewhere, especially Pacific and Indian Ocean islands. At once high resolution, approachable, and a great conversation piece, the topographic models attract crowds. The models are designed to survive repeated planning sessions involving colored dots, tape, and toothpick flags. They often remain in villages and towns to help resolve disputes and track illegal logging and other encroachments. The greatest barriers to implementing P3DM have been the scarcity of good topographic data and high-resolution images, and the inability to scan and share the 3D maps themselves. Drone technologists and programmers working on SfM (structure from motion) 3D scanning are fast solving both problems.

Public Lab's balloons and kites and P3DM maps are readily crafted objects extending the reach of mapping networks into social spaces in a way communities can control. P3DM depends on topographic surveying, now simplified by GPS satellites and algorithmically generated 3D models made from aerial imagery. Our MapKnitter software lets users stretch their aerial photos on top of existing satellite imagery, relying on existing precision satellite imagery to make higher-resolution maps. As GPS, satellite data, and imaging capabilities are encapsulated in consumer devices, it becomes easier to craft extensions of networked maps from simple materials. Community technology access is more than owning a device; it is the ability to depend on a technology's capabilities and build it into future plans, confident that the devices can be acquired and used. Every community will have different answers to the questions of accessibility in line with their available resources, especially money and time.

A good public process is an informative curiosity that attracts a crowd, whether it involves a land-use planning decision or flying to take aerial photos. Success rarely comes quickly; such processes cannot be hurried, though this should not be used as an excuse for foot-dragging.[35] When local residents are the experts, a fun and involving decision-making process will maximize the number of participants, the quality of the information presented, and ultimately the time devoted to decision-making. When flying and getting aerial imagery, local expertise is crucial to understanding both the targets to image and where to fly safely. The more time participants spent on a mapping problem, the better the results.

In many technical processes, the technical expert pigeon-holes other people in places that relate comfortably (for the expert) to the expert's professional hierarchy. Labor can be divided along expert lines, as in the fields of volunteered geographic information and citizen science, where "citizens as sensors" collect data to

Wikimedia Commons

The Gowanus Canal from Hamilton Avenue Bridge. A project called GLAM has been using aerial imagery to confirm suspicions about runoff and hidden drains.

support the researchers' questions with little thought to how the data returns to and supports the participants.[36] Instead of segregating individuals by credentials and customs, restricting their participation to different points in the inquiry process, Public Lab attempts to open all points in the process to everyone. People are encouraged—and through the collaborative nature of the community, *required*—to be involved in the process of questioning—why, how, and who—through the development of social and technical methods.[37]

Socially, Public Lab creates relationships with data advocates and environmental justice organizations to actively build data analysis and interpretation into our process to ensure that data-use decisions lie in the hands of the people collecting the data. Technically, the community works to critique and translate GIS formats in our mapping system so people can create locally impactful and bureaucratically acceptable maps from a community level.

aIn the Public Lab community, aerial mapping as a means of stakeholder engagement has been demonstrated in settings as diverse as coal terminal pollution in southeast Louisiana and land disputes in Kampala, Uganda. In Louisiana, organizers captured aerial images via kite of a coal terminal dumping into the Mississippi River. These images led to engagement on different levels. The community came to better understand coal terminal operations. The Louisiana Department of Environmental Quality visited the terminal, then filed a notice of intent to sue under the Clean Water Act. In Kampala, a women's craft market used aerial images captured by a balloon to hold off the eviction of the market. The images proved to be an effective means to communicate with government ministries involved in decision-making about access to that plot of land.[38]

CONCLUSION

Maps began as a language of the powerful. They have since become a widely used language of power with a broad range of speakers. People-centric mapping has emerged from people using existing and new technologies to counteract the observable reproduction of bias in mapping systems. Though the people-centric mapping movement did not originate with drones, drones will play an increasingly central role in people-centric mapping and science. While maps are still created in the service of centralized control for national or commercial advantage, mapmakers have both broadened access to maps and decentralized the techniques of production, distribution, and analysis. Generations of critical practitioners have made hard-won gains in people-centric mapping and recognition of its legitimacy in local practices, government processes, and international land formalization standards.

Geographers are technically oriented social scientists. People-centric mappers have worked to document systems of participatory geography and the mapping of customary land-use patterns. They've also made these programs compliant with international standards and interoperable with other geographic systems. The Social Tenure Domain Model, created by UN-Habitat, the International Association of Surveyors, and the Global Land Tool Network, is approved by the World Bank and is an approved specialization of the Land Administration Domain Model, certified by the International Organization for Standardization. Civic engagement is built around dialogue and compromise, finding the common ground needed to sustain united action. Participatory data collection is past the experimental stage. It is ready to go to be integrated into civic life as an evidence-based methodology for supporting public decision-making. §

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CHAPTER 3: DRONE REGULATION-PRIVACY AND PROPERTY RIGHTS

KONSTANTIN KAKAES

This chapter explains some general principles of drone regulation by national governments and asks how both air safety and privacy will be shaped by new technologies. It puts forth the claim that taking property rights in the air seriously is a way to allow innovation while protecting safety and privacy. The chapter is not an exhaustive discussion of the specifics of particular regulatory regimes. Up-to-date links to individual countries' regulations are available at drones.newamerica.org/#regulations

As far back as 1944, when the Chicago Convention on International Civil Aviation established the International Civil Aviation Organization (ICAO), the international umbrella body for aviation regulators, authorities were considering the implications of "pilotless aircraft." Article 8 of the convention prohibited "aircraft capable of being flown without a pilot" from trespassing over the territory of contracting states without permission and further obligated the fifty-two signatories (nearly all sovereign states now adhere to the convention) to "insure that the flight of such aircraft without a pilot in regions open to civil aircraft shall be so controlled as to obviate danger to civil aircraft."[1]

Just what it means to obviate that danger is a question that national aviation regulators around the world are wrestling with. The chief danger that unmanned aircraft pose to manned aircraft is accidental collision.* This is for two reasons. The first is the sheer number of small unmanned aircraft. There are already more small drones than exist general aviation aircraft, and that number will only grow. The air will become more crowded than ever before. The second is the limited situational awareness that drones have. Though drones can be flown with so-called "First Person View" (FPV) cameras that provide some such awareness, regulators believe (based on a track record of military drones with somewhat similar systems) that FPV systems do not provide awareness comparable to a pilot within an aircraft. (Some drone-hobbyist users of FPV systems would disagree.) At some point in the future, drones may commonly have onboard systems that algorithmically avoid collisions. The vast majority of drones do not have such systems at present.

* This is a question of numbers; hundreds of thousands of small drones are being flown without malicious intent, while there are at most a very small number of would-be attackers. Deliberately crashing a small drone into an aircraft or helicopter is difficult because of the high speed of airplanes and the downdraft helicopters create, among other factors. Would-be malicious UAV users deliberately provoking midair collisions ought not to be the main concern of regulators. There have been dozens of recorded "near misses" in recent years (see Craig Whitlock, "Near-collisions between drones, airliners surge, new FAA reports show" Washington Post, November 26, 2014). There is no reason to believe any of these were attempted attacks.

The signing of the Chicago Convention of 1944 established ICAO. Though not a major concern at the time, the convention did mention "pilotless aircraft". Image from Wikimedia Commons.

In a century of manned aviation, a number of techniques for airspace management have been developed to prevent collisions. These might sound similar to a layperson but in fact entail distinct technical solutions.

The first is to segregate airspace. If manned aircraft and unmanned aircraft fly at entirely different altitudes, then there is no risk they can collide. At worst, unmanned aircraft could collide with one another, which would not involve loss of life. This approach means excluding drones from the vicinity of airports used by manned aircraft and confining them to low altitudes where manned aircraft are already prohibited from flying. However, because of exceptions—like medevac helicopters, which must fly at low altitudes and must have freedom to go almost anywhere at short notice to complete their missions—total segregation is not possible. It is, however, the principle behind restrictions, in many jurisdictions, that confine small drones to low altitudes.

However, low-altitude flight implicates privacy; low-flying drones can more easily take pictures that infringe on privacy and can create noise that is an "intrusion upon seclusion."* Thus, some have proposed segregated bands for drone flight between, say, 500 and 700 feet above the ground that would be reserved for unmanned aircraft. Similar bands for larger unmanned aircraft at higher altitudes could segregate them from manned aircraft. If airspace control systems were being designed from scratch, such bands would be a logical solution. However, they are not likely to be implemented in any jurisdiction because they run counter to the legacy of how airspace has been regulated.

The next mechanism for preventing crashes is to maintain "separation" between aircraft. This works in controlled airspace, where air-traffic controllers keep track of where both manned and unmanned aircraft are. It allows, for example, Predator drones flown by the U.S. government to patrol the U.S.-Mexico border. It also is what has allowed the airport in Kandahar, Afghanistan, to function. The airport was for some time the world's busiest single-runway airport,[2] with more than 800 takeoffs and landings per day—civilian and military, manned and unmanned, all mixed together. Air-traffic controllers managed this airspace by keeping a minimum of 1,000 feet of separation between drones and manned aircraft and 500 feet between one drone and another.[3]

There does not exist, for the moment, a system for maintaining separation between small drones. (To the extent that drones have been integrated into air-traffic management schemes, like that in Kandahar, it has been large drones whose operators have been able to speak with air traffic controllers.) For such a system to work, controllers must be able to both see all relevant aircraft and direct them. Small drones fly at lower altitudes, where radar coverage is difficult; there are many more of them, and because small drones have very limited payload capacity, systems that allow them to interact with air-traffic control and other aircraft must be carefully designed.† NASA is developing a system that would act as a global surveillance system for small drones at low altitudes.[4] (This is, at present, by way of a technological experiment, rather than a concrete scheme to be implemented at a national level.)

As a backup in case separation measures fail, passenger aircraft are required (throughout the world) to have a Traffic Collision Avoidance System (TCAS), which is an automated system in which transponders on aircraft communicate with one another and alert pilots to the risk of collision. In smaller aircraft, a pilot's eyes can suffice—the pilot is required to be able to "see and avoid" other aircraft. Developing systems for drones to "sense and avoid" other aircraft is an active area of research, as is determining how to regulate such new technologies.[5] Some consumer drones already have limited autonomous sense-and-avoid technologies, such as DJI's "Guidance" system.6 The capabilities of such autonomous systems are changing rapidly. It is difficult to venture predictions about how they will improve. Systems that work at low speeds won't do much good at high speeds; systems that work well in controlled testing may not be resilient in the real world. However, much may change quickly.

Larger drones can carry sophisticated sensors, cameras and gimbals that give the pilot good situational awareness (though not as good as that of a pilot in a manned aircraft). The FPV systems that smaller drones have provide a similar, though more limited capability. Such FPV systems can be used to race around obstacles at high speed.[7] This does not mean, however, that they provide the sort of peripheral awareness that a pilot in an airplane cockpit has. Latency with such systems is also an issue.

Many countries, particularly in the developing world, still do not have explicit regulations governing drones. However, in the United States, Canada, Europe, Australia, and elsewhere, a broad consensus on how to regulate drones has emerged in the past decade. The similarities among the various regulatory regimes outnumber the differences. That consensus is to allow more flexibility for smaller drones. These generally can be flown at low altitudes, far from airports, far from crowds, and within the line of sight. Some countries—France, for instance—permit flight beyond the line of sight for very lightweight drones. This is sensible and likely to become more common. The United States has lagged behind the United Kingdom, France, Germany, Australia, Canada, and elsewhere in the implementation of commercial drone flight regulations, however, the proposed rules which the Federal Aviation Administration (FAA)

* "Intrusion upon seclusion" is one of the types of privacy violation enumerated in the second restatement of torts, a compendium of common law (https://cyber.law.harvard.edu/privacy/Privacy_R2d_Torts_Sections.htm). There is no clear dividing line here; sophisticated military sensors can capture a great deal of detail from thousands of feet (indeed from space). However the small, cheap cameras common on consumer drones cannot capture much detail from, say, thousands of feet in the air. These boundaries will shift as camera technology improves.

† In the future, manned aircraft will, for the most part, carry a system called ADS-B that will actively transmit their position and altitude to other aircraft and to ground controllers. However, ADS-B systems may be too heavy for small drones; the system also likely does not have the radio capacity to handle the traffic of hundreds of thousands of small drones.

issued in February 2015 are broadly similar to rules in other jurisdictions, though they will likely not take effect until late 2016 or early 2017.

There are, of course, important differences between these countries. In Japan, for instance unmanned helicopters surpassed manned helicopters as crop dusters in 2004.[8] The reason this was possible, from a regulatory perspective, is that the crop-dusting drones (the Yamaha R-Max is far and away the market leader) though heavy, fly only at low altitudes over remote farms. They are thus regulated by the Japan Agricultural Aviation Association in conjunction with the Ministry of Agriculture, Forestry and Fisheries rather than the aviation regulator. The lesson from Japan is an important one insofar as it shows that regulating flight near the ground is not necessarily best done by aviation regulators, but perhaps by whichever body is responsible for regulating the relevant patch of ground—whether this be an agriculture ministry or local law enforcement. Indeed, Japan is lagging in implementing rules for non-agricultural drones. But the logical division of airspace has allowed it to attain preeiminence in one sector.

Within the emerging consensus for the regulation of small drones, many countries maintain legacy distinctions between recreational and nonrecreational drone use as a result of the history of hobby remote-controlled aircraft.[9] Such distinctions do not hold water today; as much as possible, recreational and nonrecreational users should have to follow similar rules based on the risk of where and how they are flying. Recreational and commercial users need not be subject to identical rules; however the divergence in rules ought to be minimized.

Take regulations concerning beyond line-of-sight flying. One major concern is the reliability of the radio link that connect control systems on the ground with drones. The Radio Technical Commission for Aeronautics (RTCA) standards for command-and-control data links[10] are a first step in this direction; the final standards, due to be released in July 2016, ought to provide a solid foundation for regulators to build on. Compliance with such standards and regulations ought not to turn on whether a flight is for recreational or non-recreational purposes—a distinction that is, in any case, a problematic one to make. Many hobbyists run photography business on the side, for instance; academics may fly both for fun and for research purposes.

The key challenge for aviation regulators is to figure out how to break free of the legacy of manned aircraft regulation. A fresh start would allow regulators both to avoid some of the absurdities that result when applying manned-aircraft regulations to unmanned aircraft, and to be attuned to the new threats to privacy that drones pose. The Riga Declaration on Remotely Piloted Aircraft, a March 2015 European Union document (which is not legally binding) put this well: "Drones need to be treated as new types of aircraft with proportionate rules based on the risk of each operation."[11] As of the summer of 2015, for instance, in the United States, would-be commercial drone operators who apply for a special exemption must have a manned pilot's license, even though flying a small drone remotely has little to do with flying a Cessna.

Many argue that harmonization of drone regulations is desirable, both among states within the United States and among nations around the world. Such standardization makes things easier for the commercial drone industry. However, as Margot Kaminski, a law professor at Ohio State University, has pointed out, it also has drawbacks.[12] Balancing the right to gather information (a First Amendment right within America) of people who fly drones with the right to privacy of those who can be seen by drones is not straightforward, and there is a case to be made for allowing different jurisdictions to experiment in different ways with finding this balance.

The balance to be struck between the freedom of a drone operator to operate uninhibited and the risks to safety and privacy drones can pose entails distinct legal considerations in different countries. In general, more open debate over these issues, in both the legal system and in academia, has taken place in rich countries like the US, Canada, Australia, Western Europe and Japan. The course these debates take in these countries will affect how drones are used in the rest of the world as well.

The drone-hobbyist community, though young, has already developed a rich tradition of tinkering. (The online epicenter of this is the website diydrones.com.) Even Chinese manufacturer DJI, which makes the Phantom, the world's most popular drone, meant to be easy for beginners to fly out of the box, sells a software development kit. Drones are, in certain respects, where personal computers were in the 1980s. Tinkerers with limited resources can, through ingenuity, compete with major manufacturers who make comparable products for many multiples of the price.

This vibrancy can be ruined by overregulation—in particular, requirements that drone hardware and/or software limit where drones can fly, or so-called "geofencing."[15] Such approaches ought to be met with skepticism. Though built-in restrictions like geofencing can often be circumvented by skilled users, they nonetheless inhibit innovation, without necessarily substantially improving safety or security.

THE PROBLEM OF PERSISTENCE

Indeed, the most difficult questions regarding drone regulation are not, in the end, related to safety. Safety questions are ultimately straightforward compared with privacy questions. For instance, persistence of drones in the air is not a threat to air safety but is a threat to privacy.[16]

At present, persistent surveillance using drones is not that cheap. Small, cheap UAVs do not have the endurance necessary for persistent surveillance. As sensor packages are further miniaturized and batteries improve, this will change. The expense and technical difficulty of persistence mean that it is not now within the reach of many private actors. This too will change with new technologies such as improved solar cells and lighter-weight, increasingly more capable sensors.

There is no clear line between persistent and episodic surveillance. Any narrowly written rule proscribing persistence could be evaded by flying a series of orbits, each for some amount of time shorter than the amount put forth as the maximum duration of persistence. Thus, much like anti-loitering laws (despite the fact that such laws have been abused), the line between persistent and episodic surveillance must be left to the discretion of the courts.

However, persistent surveillance must not be allowed by nongovernmental actors. Within the United States, many Fourth Amendment protections hinge upon a "reasonable expectation of privacy." If private actors can engage in persistent surveillance, it then opens the door for the state to do so as well. Existing tort law can be used to limit persistent aerial surveillance, but only if a court finds that solitude or seclusion can be violated by drones flying for long periods overhead. Such a case has not yet come to trial. Of course, not all persistent flight would meet a reasonable definition of surveillance. Environmental monitoring flights by scientists, for instance, might have good reason to stay in the air for months at a time, propelled by electricity from solar cells.

Much of this report is devoted to the use of drones by and for people who will be affected by the information drones gather. In cases where drones are flown above people who actively consent to—and are even involved in—the flight of drones, privacy concerns are diminished. They do not disappear, since questions around who gets to access data the drone gathered remain. (Such questions are addressed in Chapter 2.) Episodic information-gathering is a more straightforward process to consent to; many individuals might tacitly consent to persistent surveillance with a shrug. Consent alone is not a sufficient condition.

Limits on persistent surveillance from drones do not resolve the many important questions raised by other forms of surveillance. Monitoring the location data generated as a byproduct of widespread mobile-phone use amounts to another form of persistent surveillance. However, persistent aerial surveillance removes yet one more type of solitude. One can, at least in principle, not drive on a highway, not carry a mobile phone, or not send mail. The state should not treat all people as suspects who have yet to commit a crime. Private persistent surveillance would only normalize the technique for law enforcement and thus should also be prohibited.

PROPERTY RIGHTS IN THE AIR

One way to limit persistent surveillance has other ancillary—and significant—benefits. As Ella Atkins, a professor of aerospace engineering at the University of Michigan, argues, within the United States, the FAA ought to take seriously a 1946 Supreme Court decision, *United States v. Causby*.[17] In that case, the court found that military planes flying low over Causby's chicken farm were violating his property rights. "If the landowner is to have full enjoyment of the land, [the landowner] must have exclusive control of the immediate reaches of the enveloping atmosphere," Justice William Douglas wrote in the majority opinion. "The landowner owns at least as much of the space above the ground as he can occupy or use in connection with the land. … [T]he flight of airplanes, which skim the surface but do not touch it, is as much an appropriation of the use of the land as a more conventionalentry upon it."

The FAA has marginalized the *Causby* decision by arguing that drones expand the definition of "navigable airspace." Previously, areas

GTUAV via Wikimedia Commons

The Yamaha R-MAX unmanned helicopter has been in widespread use in Japan since the 1990s.

above 500 feet in rural areas and above 1,000 feet in urban areas, were deemed navigable, along with takeoff and landing corridors, because manned aircraft can't fly safely at lower altitudes. However, because drones can safely fly at low altitudes, the FAA now claims the authority to regulate "down to the blade of grass." Paul Voss, an engineering professor at Amherst College asks, "Can we fly a kite anymore? These strings are tremendously dangerous to Amazon's drones. Now the FAA has to worry about that."[18] The solution, he and Atkins say, is to give property owners control over the space above their property up to something like 500 feet. Though on its surface this raises enforcement concerns, the question is what the legal regime ought to be. The fact that it could only be enforced imperfectly is secondary; the question is what norms ought to be established as drones become common.

In the short term, such an embrace of property rights in the immediate reaches of air, would allow universities to conduct experiments on university-owned land* and private tech companies to do the same on privately owned land, so long as they made sure not to venture onto other people's property. It would allow farmers to use drones to conduct crop surveys and to dust crops. It would allow Amazon and Google to experiment and develop technologies that they might one day be able to use for delivery of goods in a way that doesn't intrude on anybody's privacy. There are myriad technical problems to be solved before a widespread drone delivery network becomes feasible—weather, for instance, is a big problem at low altitude, one that is poorly understood because the aviation community hasn't had to deal with it.

REGULATIONS AND APPLICATIONS

Just as taxi services raise different regulatory issues than does commercial trucking or non-commercial driving of automobiles, the regulatory questions facing drones depends on how they are being used. Community mapping—insofar as it is done with the consent of the community, with a relatively lightweight drone flown at a relatively low altitude is more straightforward, from the aviation regulator's point of view, than a network of heavier delivery drones that would extend over a large area. Drones taking photographs of disasters—where they might come into conflict with, say, firefighting aircraft or medevac helicopters—raise another distinct set of issues.

MINORITY GAME

Many drone pioneers see regulators as the enemy. Because the number of unmanned aircraft in the air has been relatively limited, it has been possible to get away with bending the rules in uncrowded airspace. One can fly a small drone, say, over the East River in Manhattan without it harming anyone in an obvious way, even though doing so is against government regulations due to the proximity to LaGuardia Airport. However, one can do this only if drones are rare. As drones become increasingly common, rules become increasingly important. The airspace will grow more and more crowded, making rules of the road vital.

There are aspects of those rules that are conceptually challenging to figure out. But there is no need to make them more complicated than they have to be. For instance, licensing requirements for commercial operators should not be needlessly onerous. According to Quartz, to get a commercial drone license in South Africa, after new rules implemented in the early summer of 2015, "could take over two months to process, and cost you anything between $1200 and $4000, depending on the size of your drone."[19]

International regulators should talk to one another and harmonize safety standards where possible. They ought not to adopt a one-size-fits-all policy, however, as the questions regarding drones' impact on privacy must be parsed differently in different countries with different conceptions of privacy. Standardized air-surveillance systems such as NASA's NextGen system for maintaining separation of drones from one another and from manned aircraft may prove necessary, even as they chip away at freedom of the skies. The regulatory trade-offs depend very much on how the technology evolves—the need for global surveillance schemes depends on how capable decentralized sense-and-avoid systems become. The more capable individual aircraft are of sensing and avoiding obstacles such as other aircraft, the less necessary a centralized system keeping track of where—and keeping apart—everything in the sky is.

There are no simple answers here. Regulators must listen to industry in order to understand the technical trade-offs, but must also avoid simply implementing the solutions desired by the unmanned-aviation industry, which will continue to grow rapidly in size and thus in influence in regulatory debates. FPV systems, for instance, are improving. Regulators should have enough discretion to sensibly adopt rules about beyond line of sight flight using FPV systems. Industry and drone enthusiasts should also understand that regulators' caution is not entirely without merit.

Many of these debates will be shaped by drones' capacity for autonomy and will have commonalities—how to approach liability, for example—with debates over autonomy in other related sectors, for instance with regard to driverless cars. What is clear is that aviation regulation—which has evolved to deal mostly with questions of safety—must now tackle privacy as well. §

* Academic researchers in the United States seeking to fly drones outside must currently jump through a number of regulatory hoops, which differ in detail depending on whether the university in question is public or private.

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CHAPTER 4:

HOW TO MAKE MAPS WITH DRONES

FAINE GREENWOOD

Inexpensive drones are capable of making sophisticated maps. Small, portable drones are quickly deployable. They carry lightweight digital cameras that can capture good-quality images. These cameras can be set to take pictures at regular intervals, and digital memory is cheap and plentiful. After landing, the pictures can be knit into georectified orthomosaics—that is to say, they can be geometrically corrected to a uniform scale, adjusted so that they adhere to a common geographical coordinate system, and knit together.

Lightweight GPS units enable drones to make spatially accurate maps. Because there is no need for the information in real time, drones do not have to carry data links that add weight and complexity. Such drones can be used at a local level to create maps rather than having to rely on centralized mapping authorities. They complement other mapping methods and fill in imaging gaps left by satellite mapping and traditional surveying.

While drone mapping is a new practice, practitioners around the world have already begun to incorporate this new variety of aerial imagery into their work. In Tanzania, the Swiss organization Drone Adventures is creating a high-definition map of the megacity of Dar es Salaam.[1] Images shot by a fixed-wing SenseFly eBee drone have already been used by the OpenStreetMap project to accurately trace buildings and roads, improving the maps available to the local community.

In Ethiopia, researchers have used drone imagery[2] to map water sources likely to harbor the larvae of malaria-carrying mosquitoes, allowing them to be destroyed before the mosquitoes spread sickness throughout the region.

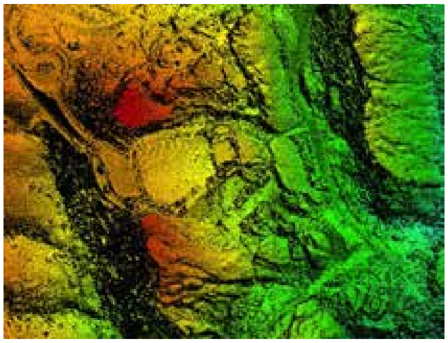
In Borneo, indigenous Dayak people have begun to use unmanned aerial vehicle (UAV) imagery[3] to document illegal use of their land and to delineate boundaries, enabling them to better defend themselves against the land-grabbing practices that are common in Southeast Asia.

However, drone operators need a high tolerance for risk and a willingness to troubleshoot. Fieldwork with mapping UAVs remains in its early days. There is room for considerable innovation, but also for unforeseen problems and technical challenges. Changing and uncertain regulation of drones also poses difficulties.

TYPES OF MAPS: ORTHOMOSAICS, 3D MODELS, OTHERS

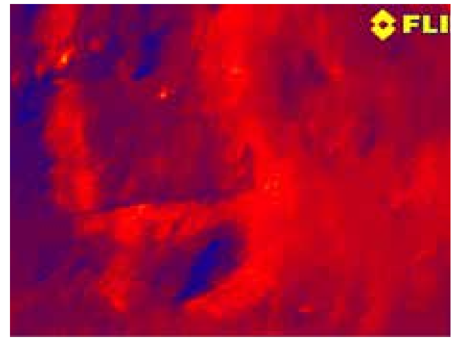
UAVs can produce a number of different types of maps: geographically accurate orthorectified two-dimensional

An orthophoto shot by Irendra Radjawali's mapping UAV documenting a dried-out lake near a bauxite mine in Indonesia's West Kalimantan province on the island of Borneo. (Image courtesy Irendra Radjawali.)



Digital elevation model — Red Rocks Amphitheatre, Colorado, obtained using a UAV

Normalized Difference Vegetation Index (NDVI) from Nov. 1, 2007, to Dec. 1, 2007, during autumn in the Northern Hemisphere



Kite aerial thermogram of the site of Ogilface Castle, Scotland

From left: DroneMapper via WikiMedia Commons, NASA image via WikiMedia Commons, John Wells via Wikimedia Commons

maps, elevation models, thermal maps, and 3D maps or models. If properly produced, these data products can be used for the practice of photogrammetry, which is most simply defined as the science of making measurements from photographs.*

Two-dimensional maps are still the most commonly created products from imagery collected by a UAV. The simplest way to create a mosaic from aerial imagery is by using photo-stitching software, which combines a series of overlapping aerial photographs into a single image. However, without geometric correction, a process that removes the perspective distortion from the aerial photos, it's hard to accurately gauge distance. Images that have been simply stitched are continuous across boundaries, but don't have perspective distortion corrected. Geometric correction is only one step in making a usable map. A modern mapmaker also wants to know what point on the map corresponds to what precise latitude and longitude on Earth. Accurately ascertaining geographical references is difficult to carry out without the aid of ground control points, accurately surveyed locations that are identifiable in the imagery.

An orthomosaic is a series of overlapping aerial photographs that have been geometrically corrected (orthorectified) to give them a uniform scale. This process removes perspective distortion from the aerial photos, making the resulting "mosaic" of 2D photographs free of distortion.

Orthorectified photos can be used to produce GIS-compatible (geographic information system) maps for archaeological applications, for construction, for cadastral surveying†, and for other applications.

3D models, which permit researchers to make volume calculations from a set of aerial images, are increasingly common outputs from UAV technology,[4] as new hardware and software have made it easier than ever to produce them. Instead of flat, two-dimensional output created by standard photo-stitching techniques, 3D models resemble video games that let you navigate virtual worlds from within.

Other data products that can be made from UAV-collected imagery include digital elevation models (DEM), NDVI (vegetation) maps, and thermal maps, which require specialized payloads and processing software.

Digital elevation models are distinct from 3D models—they are more akin to topographical maps[5]. They represent only the underlying terrain; surface features such as buildings, vegetation, and other man-made aspects are removed, revealing the underlying surface. In a digital elevation model, a given point in the plane has a unique height, so features with cavities—like buildings—cannot be adequately represented.

NDVI maps, most commonly used for agricultural applications, are made from specialized Normalized Difference Vegetation Index (NDVI) images, which are taken with cameras that can see in both the visual and the near-infrared spectrum.[6] NDVI imagery is used to assess whether a certain area has green vegetation or not, based on the amount of infrared light reflected by living plants. Standard point-and-shoot cameras, such as the Canon A490, can be modified to capture the wavelengths required for the imagery used to create NDVI images,[7] considerably bringing down the cost of gathering this data .

Thermal maps image the temperatures of a given mapping area, and are useful for applications such as detecting structural damage to roads,[8] identifying the source of groundwater discharge,[9] spotting hidden archaeological ruins,[10] and detecting roe deer fawns that may be harmed by mowing operations.[11] Specialized thermal imaging cameras, such as those made by FLIR,[12] are light enough to be mounted on a UAV and are increasingly being adopted by civilian pilots interested in gathering thermal imagery. Many of these systems remain quite expensive, and some are subject to export restrictions.[13]

FLIGHT PLANNING

Planning a mapping mission entails a number of considerations. A first-order decision is whether the flight will be done under autonomous control between GPS waypoints or will be controlled manually. In either case, it is important to analyze the area to be mapped before liftoff. The area should be walked, driven around or otherwise

* Classic photogrammetry required the use of metric cameras that had been precisely calibrated. Drone mapping instead uses a technique called "Structure from Motion" which uses the information from multiple images to obviate the need for precise camera calibration.

† A cadastre is a record of who owns what land, compiled for tax purposes.

evaluated before the mission starts so as to identify obstacles such as power lines, large trees, sensitive areas, or other potential pitfalls. Finally, it is good practice to use existing satellite imagery to plot out a flight before takeoff.

The decision of whether to use manual or autonomous control hinges on many factors, but perhaps the most important is to distinguish clearly between inspection or monitoring of events or conditions in real time, and gathering information in order to create a static record like a map or a 3D model after the flight is complete. Both types of missions can be flown in either manner, or indeed, in a hybrid of manual and automatic control, however, manual control is generally more useful for inspections (say beneath a bridge) that aim to react to information in real time, while autonomous control is, as a rule, more useful when one is trying to fly in a systematic pattern to create a map.

The majority of UAV mappers use autonomous control, though some pilots fly their missions entirely manually, relying on their own skill and judgment instead of trusting the computer. Pilots should know how to competently fly their UAV, even if they do plan to use it primarily for autonomous missions. UAVs should remain within the visual line of sight of pilots unless the pilots have sufficient experience, specific need, and regulatory approval to fly beyond their line of sight.*

If something goes wrong with the autonomous system, the pilot should be able to take over manual control or engage an appropriate fail-safe, like an emergency parachute. At present, commercially available autopilots do not have sophisticated sense-and-avoid capabilities, and are limited to flying from one preset waypoint to another. (Algorithmic sense-and-avoid capabilities are, however, improving.)

Those who choose to fly their missions manually, in entirety or at least in part, say it is because software for autonomous flight is not always reliable under every condition. GPS interference, bad weather, or simple technical error can cause the UAV to behave erratically. Proponents of manual flight also note that it is easier to manually fly a UAV in particularly tight and unpredictable areas, such as below forest canopies or in busy urban areas, with manual control permitting changes in course and altitude to be made more quickly. Partisans of autopilots say that using an autopilot is in fact safer because it reduces the possibility of human error and of radio interference disrupting the signal between a manual controller on the ground and the drone.

Some countries require that UAV operators be able to take manual control at all times in case there is a software malfunction or other issue. It's important to check the regulations in your planned area of operation before flying.

* This is not a hard and fast rule; experience and need are certainly necessary conditions, but there may be circumstances under which regulatory approval is impossible but flight beyond the line of sight nevertheless makes sense. So-called first-person view (FPV) systems that allow a drone operator to see from the drone's perspective are growing in popularity. The capability of FPV systems for replacing direct visual observation is an area of acrimonious debate.

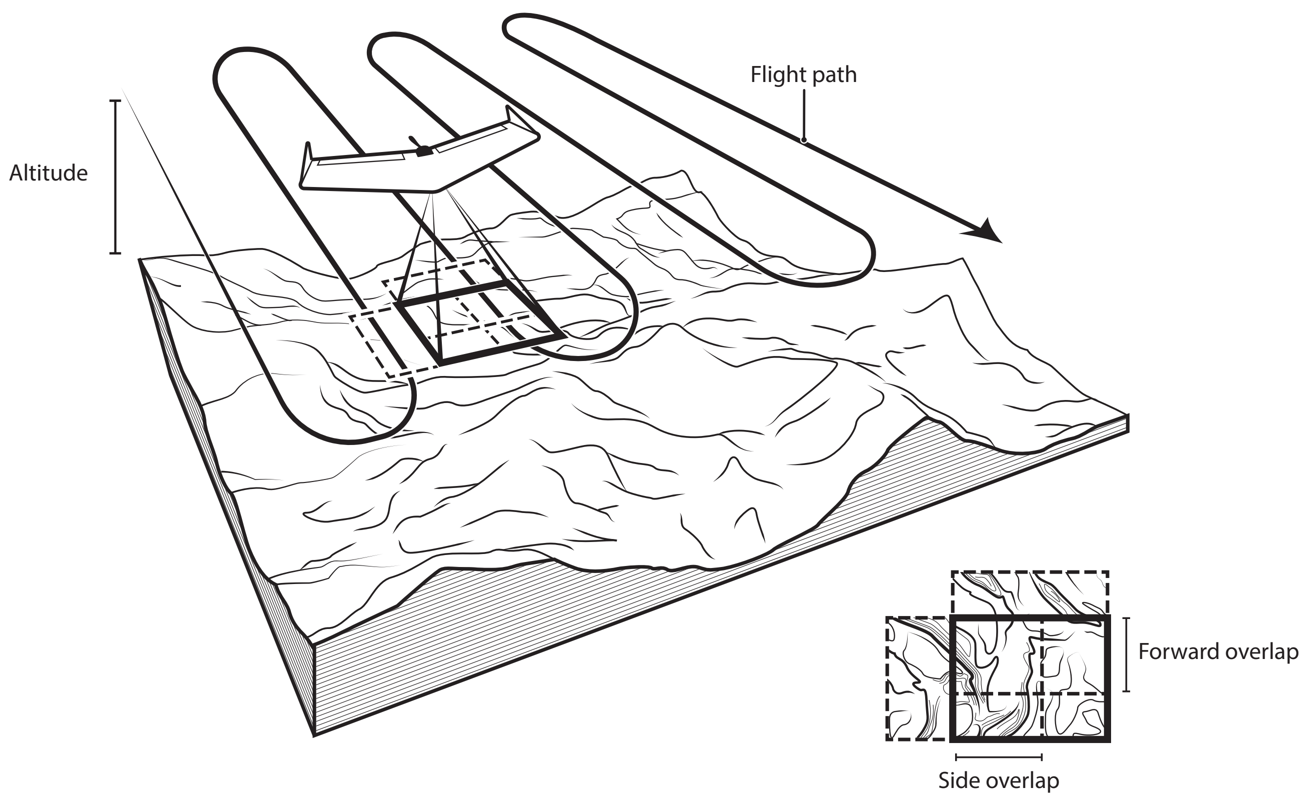


Illustration ©Valerie Altounian

UAV mapping missions are designed to ensure each image adequately overlaps with subsequent images, making it possible for processing software to merge the images.

DESIGNING A FLIGHT ROUTE

The design of flight paths is an important component of UAV mapping. This is typically done using software packages; many drone manufacturers offer proprietary software with their drones. Mission Planner, an open-source software package, is the single most widely used solution. The functionality of several competing software packages is broadly similar.

UAV mapping missions are usually flown in a specific pattern of parallel lines, commonly described as "transects," which are connected to a series of "waypoints"—think of a connect-the-dots pattern of parallel lines, or the pattern in which you might mow the lawn. A transect flight pattern is a method of ensuring that the UAV captures an adequate quantity of images that overlap to the degree required for the processing software to create a high-quality and accurate map.*

For maximum quality, some UAV mappers suggest flying two different overlapping patterns over the same area but at different heights.[14] This method collects a large quantity of data and helps to resolve elevation variation problems, which result when tall geographic features throw off the scale of the rest of the image. Others recommend adjusting the altitude of the drone to keep a constant altitude above ground level, even as features on the ground vary in altitude.

To create a flight plan with transects using current software such as Mission Planner, the pilot first connects with the UAV's flight controller via either a ground control radio attached by USB cable to a computer or tablet, or a direct USB link from the UAV to the computer.[15] (Flight plans can also be generated on the computer and uploaded to the flight controller later). The pilot opens the software and defines an area to be mapped with a polygon, then specifies the camera model, the desired operational altitude, and how the camera will be triggered to take photographs.

Once these factors are entered, Mission Planner generates a series of transects with waypoints and displays the estimated ground sampling distance, required number of photographs, and other useful information. The user can then change the distance between each photo, the amount that photos will overlap, the altitude of operation, and other parameters. The software also attempts to compensate for the effects of wind.[16]

All these numbers can be experimented with before leaving for the flight area, making it relatively easy to plan. When complete, the mission file is saved to the computer and can also be saved to the UAV's flight controller. If there is a working Internet connection available, missions can be planned at the site of the anticipated fieldwork. Otherwise, it's possible to save the planned mission to the computer to access while in the field.

Once in the field, the operator can, by the flick of a switch on an RC transmitter or computer, launch the drone. During the mission, software displays in-flight data on computer or tablet screens, including altitude, GPS status, battery status, and ground signal status.

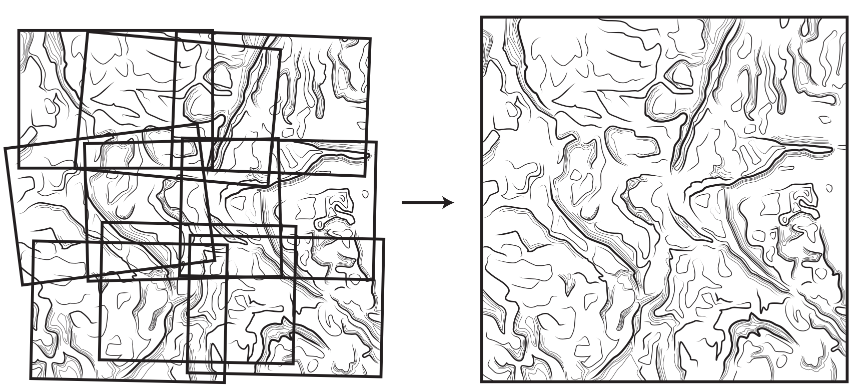
IMAGE OVERLAP

UAV flight paths or mapping projects should be designed to ensure a sufficient amount of both forward and lateral photographic overlap, which will better allow post-processing software to identify common points between each image. There is no universally accepted overlap standard, as higher or lower figures may be appropriate for different situations, such as heavily forested areas or relatively featureless landscapes.

As an example, Walter Volkmann of Micro Aerial Projects suggests overlaps of 80 percent (forward) and 70 percent (lateral/side),[17] which will produce enough overlapping photographs for post-processing software to work with. P. Barry and R. Coakley of Ireland's Baseline Surveys[18] suggest a "lawnmower track" pattern with an 80 percent forward and 80 percent lateral/side overlap. Pix4D on its website suggests at least 75 percent forward overlap and 60 percent lateral/side overlap.[19]

To achieve a certain image overlap, pilots need to balance the speed of flight with the interval at which the camera is taking pictures, as well as the altitude of the flight, the distance between the transects, and the internal geometry of the camera being used.[20] Today's flight planning software will automatically calculate all these figures for you, which is a considerable time-saver. It is, however, useful to know the underlying logic.

First, mission planning software computes the ground coverage size or "footprint" of the photograph, which is dependent on the camera's focal length, the size of its CCD



Processing software combines many photographs into a single orthomosiac image, which can then be geometrically corrected (orthorectified) and made to adhere to a real world coordinate system (georeferenced).

Illustration ©Valerie Altounian

* In some cases, one might want to map, say, a river or a road, in which case the flight pattern would be less of a grid and more of a single out-and-back path. Also, other applications in which covering a large area quickly is more important than systematic photograph overlap, for instance search and rescue, call for different patterns.

array (sensor), and how high the UAV is flying above ground level.[21]

From this ground coverage calculation, the software is able to work out how many flight paths will be needed to cover the area the user wants to map with the given camera, and will determine the spacing needed between these flight lines to ensure adequate overlap. The software then determines the minimum number of images needed to adequately cover this area, as well as the most suitable flight altitude to ensure adequate coverage as well as a sharp ground resolution.

As an example of these calculations, archaeologists from the University of Arkansas and the University of North Florida used a CineStar 8 octocopter UAV[22] to carry out thermal mapping of New Mexico's Blue J Chaco-period archaeological site in 2013. Using CineStar's proprietary mission planning software, the archaeologists conducted their survey of the area with eight east-west oriented transects of 300 meters in length spaced 20 meters apart from one another, with the drone flying at 11.2 miles per hour.

The UAV flew at an altitude of 70 meters, giving the FLIR camera with its 19 mm focal length and 8.70 X 10.88 mm sensor an image footprint of approximately 32 X 40 meters, and a ground resolution between 6 and 7 centimeters. The FLIR thermal camera was aligned perpendicular to the flight path, reducing the number of transects required to cover the area.

In densely forested areas it is difficult for the processing software to find common points among overlapping photographs; in these situations, mapping UAV makers at SenseFly suggest designing flights with at least 85 percent frontal overlap and at least 70 percent side overlap.[23] Higher overlap figures mean the UAV must take more flight paths, which will make the flight longer. They also mean that the UAV must take more pictures, which should be accounted for in processing time and in one's computer storage space.

There is no real standard for how many images to take, although more images will improve overlap and help produce better results in post-processing. Shooting more pictures also allows more pictures to be safely thrown out, such as images that are blurred or obscured by a cloud. As an example, researchers from the University of Tasmania carrying out a mapping project used a Canon 550D mounted on a heavy-lift octocopter, which was set to automatically take a photograph every 1.5 seconds. During a test of this platform in April 2012, researchers shot 297 images covering 1.9 acres.

FLIGHT PLANNING FOR IMAGE QUALITY

When it comes to mission planning, image resolution is an extremely important consideration, as collecting visual data is the entire point of the flight. Achieving good resolution in UAV photography depends on how high the drone is flying and the type (physical size and number of pixels) of the digital sensor used—typically a CCD (charge-coupled device) or CMOS (complementary metal-oxide semiconductor)—as well as the focal length of the lens, shutter speed, aperture, ISO sensitivity, and other camera settings.

Though this sounds complex, the good news is that today's mission planning software will do the calculations for you, with an interface enabling the user to specify the area to be mapped, then enter the image-quality requirements. The required image quality also varies widely. Some projects, such as archaeological surveys or aerial photography for cadastral surveying, require extremely clear images. On the other hand, say, in the aftermath of a natural disaster, image quality is less important than turnaround time. Here is an explanation of the concepts behind image resolution and drone flight planning.

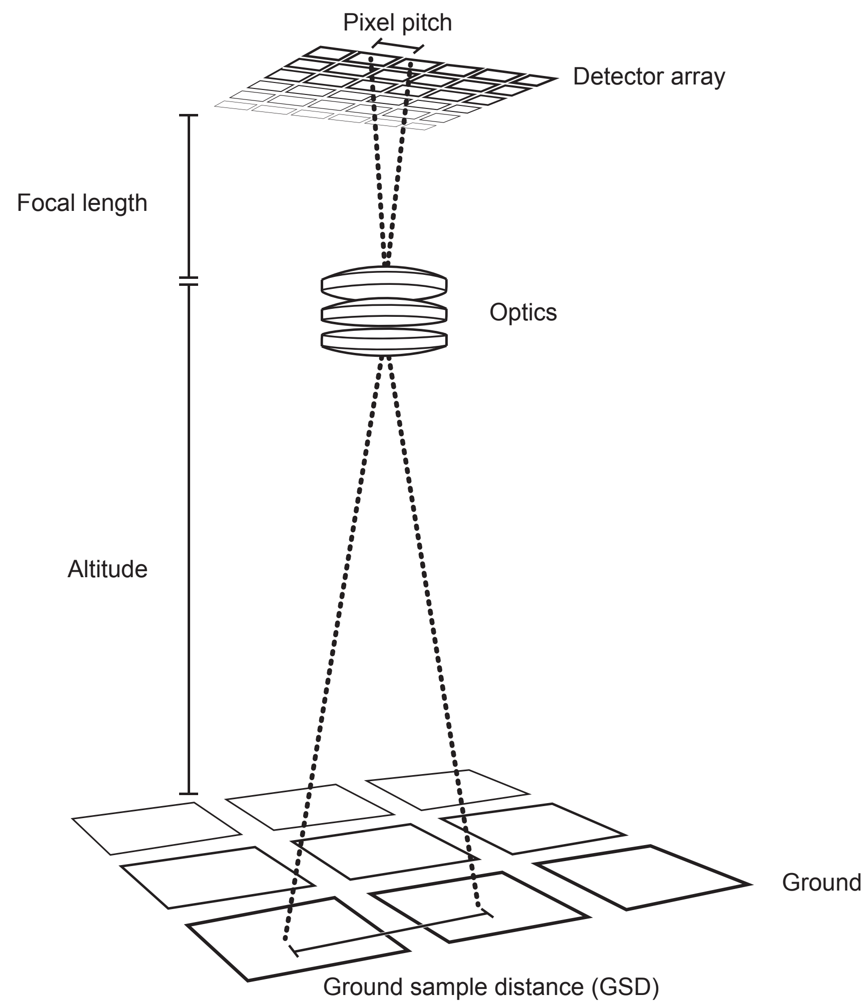
Resolution in aerial photography is measured as ground sampling distance (GSD)—the length on the ground corresponding to the side of one pixel in the image, or the distance between pixel centers measured on the ground (these are equivalent). A larger GSD (10 cm) means that fewer details will be resolvable in the image and it will be of lower quality, while a smaller GSD (5 cm) means the exact opposite. GSD goes up as the drone flies higher and goes down as the drone flies lower. GSD is also affected by the camera's focal length, as well as its pixel size.

As an example of GSD measurements in real-world mapping situations, researchers in Spain made a map using a MAVinci Sirius 1 fixed-wing UAV, paired with a Panasonic Lumix GX1 16 MP digital camera and 20 mm lens.[24] To achieve the desired GSD of 3 cm for the entire mapping area, the UAV was flown at an average altitude of 185 meters (607 feet) above the surface. The researchers wanted to gather higher-resolution data of a certain area, so they lowered the altitude to 90 meters to achieve a GSD of 1.6 cm.

How do you determine GSD for your own mapping missions? The standard practice is to determine what resolution, or GSD, is desired, then choose an altitude as a function of the hardware setup. However, it's possible to input the altitude, the size and number of pixels, and the focal length to determine which GSD a certain combination will deliver.

The calculation of ground sampling distance is in simplest terms a question of geometry. Focusing an image on a plane creates two similar isosceles triangles.* The larger triangle's height is the drone's altitude above the ground. Its width is the actual width on the ground of the region being imaged. The smaller triangle's height is the focal length of the lens being used, and its width is the width of the image inside the camera—in other words, the size of the sensor. It should be noted that sensors, and pictures, typically are not square, so the resolution in the horizontal and vertical directions is not necessarily the same. But generally they will be close to each other, as there are different numbers of pixels in the

* In fact, the act of focusing creates an infinite number of such pairs of triangles, but we can consider any individual pair without loss of generality.



An image's ground sampling distance (GSD) depends on the camera's pixel size, the UAV's altitude above the ground, and the camera's focal length.

Illustration ©Valerie Altounian

vertical and horizontal directions, so it is usually acceptable to do this calculation for one direction only.

Commercial CCD and CMOS sensors range in size from about 6 mm on the diagonal for cheap point-and-shoot cameras to 28.4 mm for so-called APS-C sized sensors (typically found in DSLRs that cost around $1,000) to 48.3 mm for "full-frame" sensors, which are close in size to a negative of 35 mm film. The physical size of a pixel is simply the length (or width) of a sensor divided by the number of pixels the sensor is capturing in the vertical (or horizontal) direction.

Take, for instance, a Canon S100—an above-average point-and-shoot camera commonly used in UAV mapping because of its light weight and ability to take pictures at regular intervals.[25] The S100 has a 1/1.7-inch sensor (7.6 mm by 5.7 mm) and can take pictures of up to 4,000 by 3,000 pixels. So the size of a pixel on the sensor is 0.0019 mm by 0.0019 mm.

By contrast, an expensive (and comparatively heavy) full-frame camera like a Nikon D600 has a pixel size of 0.00597 mm per side, about nine times bigger in area, or three times longer on each side.[26] This does not, however, mean that you can fly three times as high and achieve the same results.

Put simply:

GSD = (pixel size x height above ground level) / focal length

An S100 lens, zoomed out, has a focal length of 5.2 mm (26 mm zoomed in). So if we wanted, say, to be able to resolve 1 cm-sized features on the ground using a zoomed-out S100, we would have to fly at

1 cm x 5.2 mm / 0.0019 mm = 27.3 m = 89.7 feet

Zooming the lens all the way in would allow comparable resolution images from an altitude five times as high.

All else being equal, larger pixels allow you to fly proportionately higher, although cameras with larger sensors also tend to be heavier, which decreases flight times. There's another consideration: Larger pixels usually come with a larger total sensor area, which changes the effective focal length of the lens, varying with (roughly) the square root of the sensor area. A 5.2 mm focal length lens for a full-frame camera, if one existed, would give an extreme fisheye effect, which wouldn't be of much use for making a map.

The equivalent of a 5.2 mm lens on a camera with a 1/1.7-inch sensor like a Canon S100 is a 24 mm lens on a full-frame camera like a Nikon D600. In layman's terms, this gives the same level of "zoom." Repeating the calculation, to obtain a 1 cm GSD with the larger camera we get the necessary height of:

1 cm x 24 mm / 0.00597 mm = 40.2 m = 131.89 feet

However, the larger pixel size means the sensor will be more sensitive, allowing for a faster shutter speed in given light conditions and better image quality generally. In doing such calculations, one should always be mindful of the units of measurement, keeping an eye out for meters, centimeters, and millimeters, as well as conversions from metric. Some browser-based calculators will figure out GSD and pixel size for you.[27]

Of course, image quality is not purely a function of the theoretical resolution. A higher altitude won't be useful if there are clouds between the camera and the ground. Also, images can be made blurry by the motion of the drone. DroneMapper suggests in its submission guidelines that "a good rule of thumb to use is the camera shutter speed should be set at no lower than the time to move one half of a pixel."[28] In practice, aiming for 1/1000 of a second or faster will be more than good enough, and if there is remaining

CAMERA NAME	PIXEL SIZE	FOCAL LENGTH RANGE	SENSOR SIZE	APPROXIMATE PRICE	WEIGHT
Canon S100	0.0019 mm	24-120 mm equivalent	7.6 x 5.7 mm	$299	6.82 oz.
Canon SX260	0.0023 mm	25–500 mm equivalent	6.17 x 4.55 mm	$379	8.15 oz.
Sony Cyber-shot DSC-WX150	0.00125 mm	25–250 mm equivalent	6.17 x 4.55 mm	$174 (refurbished)	5.7 oz.
Sony Alpha NEX-7 (with 18-55mm lens)	0.00389 mm	18-55 mm equivalent	23.5 x 15.6 mm	$1,099	10.3 oz.
Panasonic LUMIX DMC-G3	0.003769 mm	Swappable lenses	17.3 x 13.0 mm	$349 (body)	19.2 oz.

Cameras that are commonly used in UAV mapping. The DSC-WX150 is no longer available new, but remains a popular choice

blur, reducing the speed of the UAV's flight should help solve the problem.

Blur induced by the drone's flight is just one factor; another is turbulence, which can be ameliorated by gimbal systems that stabilize the camera's motion with respect to that of the airframe.

SENSORS

Drone mappers use a wide range of cameras for their missions. Most cameras used for UAV mapping are lightweight and can be programmed to shoot pictures at regular intervals or controlled remotely. Some specialized devices that can be mounted on a UAV include LIDAR (light detection and ranging) sensors, infrared cameras equipped for thermal imaging, and air-sampling sensors.

The cameras required to carry out good mapping work are not necessarily the same as those used for professional video or photography work. Cameras with wide-angle lenses, like the GoPro, are very popular for video and photography uses. However, these lenses create distortion that isn't ideal for mapping work and has to be edited out in post-processing, meaning they're not well suited to this kind of project. The same fisheye consideration goes for the proprietary cameras that are paired with some commercial UAVs, such as the DJI Phantom Vision and Vision+ product line.

The internal GPS functionality of Canon's lightweight S100 and SX260 models makes them particularly popular for UAV mapping.[29] They can be used with the Canon Hack Development Kit,[30] which can program the camera to take pictures at a certain interval or to take a picture based on distance or upon encountering a certain waypoint .

Mounting the camera to the drone can be accomplished in various ways. As drone mapping is generally performed at only one or two angles, gimbals may be relatively simple as compared to those used by filmmakers. Motorized gimbals provide image stabilization, which can help compensate for turbulence and produce clearer imagery. Gimbals are also used for changing the angle of the camera from vertical (straight down) to oblique. Some mappers do not use gimbals at all or construct their own from other components.

ALTITUDE

Altitude is an important consideration when flying a mapping UAV, both for practical purposes and in the interest of flying safely and legally. Although higher altitude results in lower resolution, it allows the UAV to fly tracks that are farther apart. Higher-altitude photography also can help reduce the distortion found in images of buildings and other objects on the ground. While lower-altitude photography increases the GSD and thus the image quality, it also increases the time required to map a certain area.

Aside from trade-offs in method, legality is a paramount consideration when picking an operating altitude. In many countries it is illegal to fly above 500 feet (400 feet in some cases) or 150 meters. Prudence should always be used when flying at higher altitudes, even if local regulations do not prohibit higher-altitude flight outright. It is the drone operator's responsibility to make sure flights do not get in the way of manned aircraft.

VIEWS

The two aerial views most commonly used in UAV mapping are known as nadir (overhead) and oblique. Nadir photographs are shot directly above the subject, with the camera looking straight down. This is the perspective most associated with a traditional map. Oblique photographs are taken at an angle to the subject below, rather than from directly overhead. They can be taken from a high or a low angle, collecting information about the landscape that overhead photos cannot, and vice versa.

Photos taken from these two different angles can be combined in photogrammetry software (such as Agisoft PhotoScan or Pix4D[31]), creating imagery that gives users the ability to view and manipulate multiple perspectives in a single computer-generated model. Such three-dimensional modelscan be used for post-disaster damage assessment, accurate urban modeling, and creating more accurate flood simulations, among other projects.[32] During each flight, the angle of the camera shouldn't change, as this will make the resulting images considerably more difficult to process.

GPS AND GEOREFERENCING

Georeferencing is an essential process if you want your UAV map to adhere to a real-world scale. In simplest terms, georeferencing is the "process of assigning spatial coordinates to data that is spatial in nature, but has no explicit geographic coordinate system."[33]

While it's possible to create maps without any georeferencing, these maps do not correlate to the real world and can't be used for measurement. Georeferenced UAV maps are also much easier to work with, as they can be overlaid on existing coordinates in software. Professional UAV mapping projects almost always georeference their work.

To carry out the process of georeferencing, the image-processing software has to know the real-world GPS coordinates of a small number of visibly identifiable locations in the collected aerial imagery. These coordinates are referred to as "ground control points" in the UAV mapping context, and knowing how to collect them, and why, is an important part of understanding the process.* (The next section goes into more detail on ground control point selection.)

It is important to determine the accuracy necessary for each mission, as both overdoing it and underdoing it can have some serious drawbacks. Some maps must be accurately georeferenced using GPS technology, permitting them to be used as an accurate overlay on GIS software and in mapping applications like OpenStreetMap and Google Maps. For other uses, however, maps do not need to be painstakingly georeferenced and can instead provide a more general overview of the terrain. In these cases it may not be necessary to invest in expensive UAV hardware and software.

As an example, Indonesian geographer Irendra Radjawali uses a UAV to help the indigenous Dayak people of Borneo document the boundaries of their land and track deforestation and other illegal usage.[34] In 2014, Radjawali mapped 30 hectares of land in West Kalimantan with a tricopter equipped with a Canon SX260 camera with an internal GPS. The Dayaks said their land had been damaged by a bauxite mining operation. As Radjawali's goal was simply to document the damage, he did not use surveyed ground control points—specific, accurately surveyed points on the terrain—to create the map, but instead relied on the GPS inside the camera, as well as his hand-held Magellan eXplorist 310 GPS. The resulting map, processed in VisualSFM, was accurate enough to show the general location of the mining damage.

On the other end of the scale, researchers from the University of Twente in the Netherlands wanted to use a UAV to map customary land-use parcels in Namibia.[35] As the goal of the mission was to produce an inexpensive and accurate property map that could be used for the adjudication of land borders, geographical precision was a very important consideration. To that end, the researchers designated and surveyed a total of 23 ground control points throughout the area to be mapped. The numerous ground control points were used to ensure that some would remain if the markers were blown away by the wind or removed by local people. The mission was a success, producing a map that could be used for enforcing customary land rights boundaries.

In some cases, GPS receivers and IMUs (inertial measurement units) whose intended use is navigation and control are accurate enough to produce usable results for mapping.[36] However, many simple drones do not log their GPS coordinates, but merely use the onboard GPS to feed data into the autopilot system. GPS loggers, such as the Flytrex Core 2 Flight Tracker[37], collect longitude, latitude, and altitude values during flight, using the same GPS chip used for navigation, in data formats that can be used to help georeference maps.

Some digital cameras, such as the Canon S100, come with the ability to track the GPS location of where each image was captured, producing data that can then be used to georeference the image with processing software—although the positional accuracy is not as high as that obtained with ground control points.

Some UAVs use direct georeferencing techniques that do not require the use of ground control points, including specialized mapping UAVs such as the MAVinci SIRIUS Pro and the SenseFly eBee RTK model. Real Time Kinematic (RTK) satellite navigation is a positioning technique[38] capable of producing survey-grade accurate results down to the centimeter level by measuring the phase of the radio wave sent by GPS satellites. Other GPS mapping systems with a high degree of accuracy include the Micro Aerial Projects V-Map system, which uses dual-frequency GPS to achieve centimeter-level positional accuracy.[39]

RTK and dual-frequency techniques are especially useful for mapping areas (such as deserts or plains) that lack identifying features that could be used to create ground control points. However, UAVs equipped with RTK or dual frequency remain very expensive relative to lower-cost GPS solutions, and they probably are necessary only for high-precision mapping projects. As an example of the price difference, the SenseFly eBee RTK system costs $25,000,[40] while the standard eBee costs about $12,000.[41]

* It is also possible, using more sophisticated onboard GPS units, to create accurate maps without reference points on the ground.

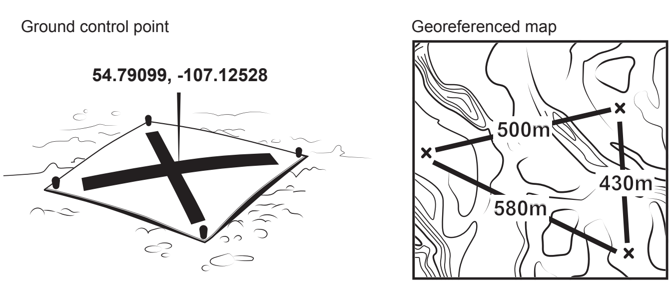
GROUND CONTROL POINTS

To get geospatially accurate survey-grade maps without expensive platforms like the eBee requires the use of ground control points. A ground control point, as previously mentioned, is a target in the desired mapping area with known coordinates, which can be used to find the coordinates of other locations on the map. A minimum number of ground control points (around five) is generally required by the software for the referencing process to function. More ground control points permit more accurate results. Ground control points cannot be clustered, but have to be scattered around the area to be mapped for best results; think of attaching a poster to a wall with thumbtacks.

Most commonly, UAV mappers who need very precise georeferencing will survey their ground control points with a professional-grade GNSS (global navigation satellite system) device, capable of locating coordinates with submeter accuracy. This device can use GPS or one of its competitors—the Russian GLONASS, European Galileo, or Chinese BeiDou. The surveyed points typically are marked before the UAV flight takes place, using easy-to-see aerial targets that later can be flagged inside of the processing software.

While ground control points are useful for increasing the accuracy of georeferencing, most photogrammetry software packages, such as Agisoft PhotoScan[42] and Pix4D, can function without them. Instead they use GPS data collected by a GPS logger or by a GPS-enabled camera to create a reasonably geographically accurate image. As an example, a 2014 forest mapping project in the Democratic Republic of the Congo[43] found that a DJI Phantom UAV equipped with a Canon S100 camera (with an internal GPS) was able to obtain position accuracy of about 5 meters.

There is another work-around for cameras that don't have GPS functionality: With the location data collected by the UAV's own GPS, which is stored in the flight log generated by the flight controller, it's possible to match the time stamp of each photograph to the corresponding location of the UAV.[44] A recent study with SenseFly's swinglet CAM mini-UAV found that the accuracy of the resulting geotags was between 5 and 10 meters in position,[45] which while not superb is likely adequate for some projects.



Accurately surveyed ground control points are used to georeference ortho-mosiac maps produced from UAV imagery.

Illustration ©Valerie Altounian

Without access to a survey-grade GNSS system that would permit them to take ground control points in the field, UAV mappers can also use ground control points taken from high-accuracy sources (such as laser scans and maps) that portray the same area, or gather them from Web map services like Google Earth or Bing. With these Web services, it's possible to pick out features in the landscape that the drone mapped and to lay place marks[46] within Google Earth, which can then be exported to photo-processing software. Additionally, mappers can buy pre-collected ground control points from services such as CompassData.[47]

3D MODELS

3D models can be generated from either nadir imagery (shot vertically, straight down) or oblique imagery (from an angle to the side), but the most detailed models combine both into a single representation. To generate a 3D map, software requires hundreds of overlapping still images.

As an example of the usual 3D-model creation workflow, Agisoft PhotoScan* software[48] first carries out the automatic process of photo alignment by searching for common points on photographs and matching them. It also deduces the position of the camera for each picture so that it can refine its camera calibration parameters.†

Once photo alignment is completed, the software generates a sparse point cloud with a set of associated camera positions and internal camera parameters. A point cloud is exactly what it sounds like—a set of points in 3D space, where each point, in addition to its coordinates, may have additional information such as color. A sparse point cloud is simply such a point cloud with relatively few points. A sparse cloud may be adequate to produce a less detailed 3D model that doesn't need to be precisely georeferenced.

Agisoft PhotoScan requires this set of camera positions and an optimized sparse point cloud to advance in the process of producing a dense point cloud, which can often take as long as 15 hours on a reasonably high-powered laptop.

Next, the software builds a 3D polygonal "mesh" based on the dense point cloud, representing the surface of the object—think of a net thrown over a three-dimensional object. In the final step, the software lays texture taken from the original photographs over the 3D mesh, giving the original flat imagery a sense of depth and volume.

The final outcome is a detailed 3D model that can be used for a variety of specialized analyses, including archaeological research, the creation of flooding models, and disaster damage assessment.

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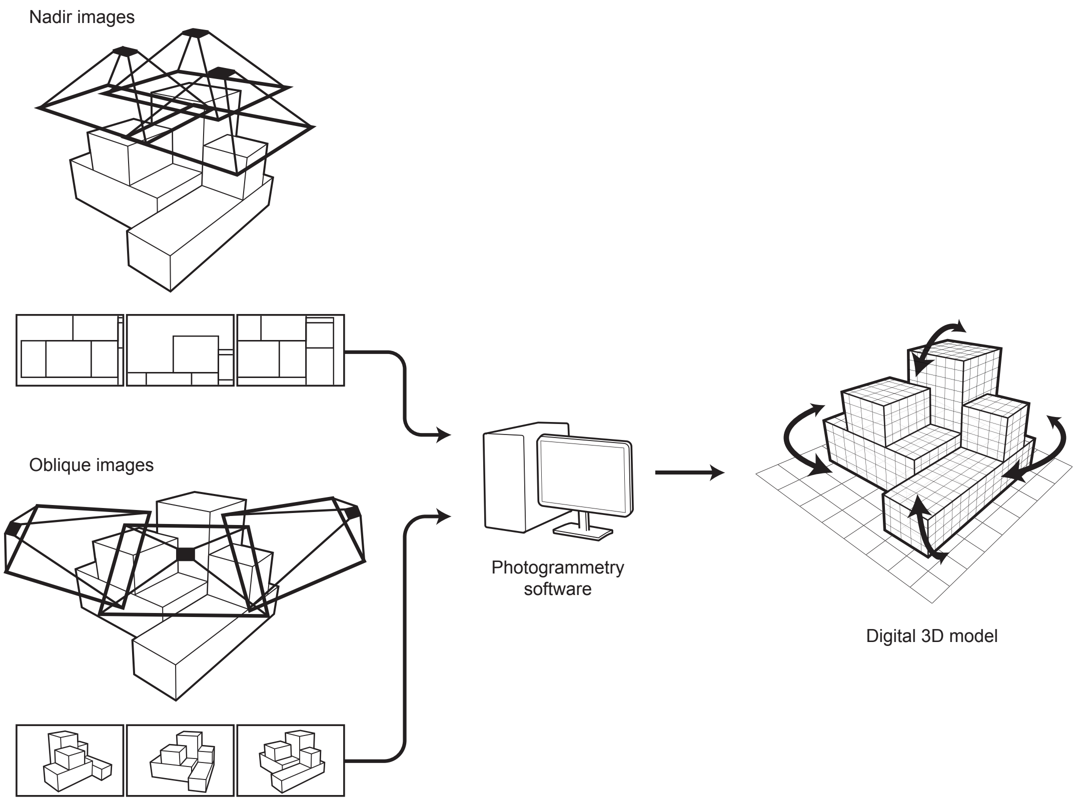
* Agisoft PhotoScan and Pix4D dominate the market for paid map-creation software; various open-source solutions also exist and will be discussed in more detail later in this chapter.

† Camera calibration in 3D computer vision is a complex process. A good explanation is provided by Z. Zhang in ""Camera Calibration", Chapter 2, pages 4-43, in G. Medioni and S.B. Kang, eds., Emerging Topics in Computer Vision, Prentice Hall Professional Technical Reference, 2004, http://research.microsoft.com/en-us/um/people/zhang/Papers/Camera%20Calibration%20-%20book%20chapter.pdf



Photogrammetry software combines information from multiple images taken from both overhead and to the side to create 3D models.

Illustration ©Valerie Altounian

(VisualSFM). Microsoft ICE (Image Composite Editor) is an established choice for panoramic image stitching, although it does not create geometrically corrected orthophotos.

Such open-source and free software packages can be more difficult to use and may have fewer features than their paid counterparts, but they are nonetheless powerful enough to achieve useful results. The Flight Riot website (http://flightriot.com) provides a comprehensive overview of open-source mapping software and associated techniques, with instructions on the proper use and selection of cameras, UAV platforms, and processing software.

PROCESSING SOFTWARE

"Having images is not the same as having a map," observes UAV mapper Cristiano Giovando of the Humanitarian OpenStreetMap Team,[49] and he's right. Collected imagery must be processed on a computer to generate a map. Choosing a software package is highly dependent on your budget, the processing power you have available, and what you want to accomplish. There is some variety in the processing software used for UAV mapping, and the market is changing as UAVs increase in popularity.

As of this writing, Pix4D and Agisoft PhotoScan are the two most popular paid aerial imagery and photogrammetry processing choices, with relatively simple user interfaces and comprehensible manuals, as well as an established track record of use for professional aerial mapping applications. Both programs are regularly updated and improved upon, as the demand for UAV mapping and the market for photogrammetry software expand. However, paid photogrammetry software is expensive and can require considerable processing power to operate, which should be factored into mapping budgets. At the time of writing (July 2015), Pix4D was priced at $8,700 for a full license and could be rented for $3,500 a year.[50] Agisoft PhotoScan cost $3,499 for the Professional Edition, while the less feature-rich Standard Edition was priced at $179.[51]

Open-source software is another possibility for aerial imagery post-processing, including MapKnitter from Public Lab, OpenDroneMap, and Visual Software from Motion

Processing big batches of high-definition aerial imagery can be slow, and depending on how many images are being used, this can require a powerful computer processor. Some field workers will do low-quality image processing in the field to check that they have shot an adequate number of images with adequate overlap, then create a higher-quality model when they return to their computing workstations.

In particular for scientific applications requiring precision, care must be taken to avoid systematic errors created by processing software. For instance, the combination of radial lens distortion and many images taken from near-parallel directions can introduce an effect called "doming," which makes a flat surface into a dome.[52]

SOFTWARE AT WORK

Drone journalist Ben Kreimer used Agisoft PhotoScan to create a 3D model of an ancient Roman site in Turkey, using photographs he had shot with his Phantom 2 and a Canon SX260 camera.[53] The software used 249 of these images to generate the model. With Kreimer's MacBook Air with a 1.7 GHz Intel Core i7 processor, a solid-state hard drive, and 8 GB of RAM, Agisoft PhotoScan took eight hours to create the model. Another model, which involved 949 images, took about 30 hours to assemble with the same computer.

In another example of the photo processing process, Austin "Chad" Hill of the "Follow the Pots" project has a two-part workflow: one for fieldwork, the other for processing work back in the office.[54] While in the field, Hill checks his photo sets to ensure that his UAV has shot enough images to create a complete 3D model in Agisoft PhotoScan upon his return to his U.S. computing station. Hill uses a late-2011 13-inch MacBook Pro, run off a generator, to process images in Agisoft PhotoScan at the lowest quality level, allowing him to make sure that a later, higher-quality model won't have any coverage "holes." These "quick and dirty checks," as he described them in an e-mail, can be processed in one to two hours with his laptop.

Back in the office, Hill uses an overclocked Haswell i7 processor with 32 GB of RAM and a modest GPU (graphics processor unit) to process UAV images in Agisoft PhotoScan, as well as to carry out GIS work with the resulting mapping products. Hill begins by processing the photos at a low level of quality in PhotoScan, which usually takes around two hours. He then carries out the georeferencing process, including identifying ground control points and checking for errors, and repeats the process at a higher quality level within the software. Per Hill, a drone photoset with a few hundred images can take as long as two days to process into final orthophotos and digital elevation models, with the computer running overnight.

Factoring in the time required to process data is an important consideration for fieldwork, as processing presents a technical barrier to projects that require a swift turnaround. To avoid unpleasant surprises, it is best to get a clear sense of how long processing will take with the computing equipment available before heading into the field.

Some companies now offer UAV mapping software that carries out real-time image processing on their servers, such as DroneDeploy, DroneMapper, and Airware. Outsourcing the computing power to process detailed UAV imagery lessens the lengthy processing time required by other photogrammetry software, and it can also provide output quickly while a team is still in the field.

However, using these services requires access to mobile data or the Internet, which is often unavailable in remote areas or during disasters. Some services, such as DroneDeploy, require the purchase of a separate unit that is mounted on the UAV to function. As an example of pricing for these services, DroneMapper, as of June 2015, charged $60 to process imagery equivalent to an area of about 3 square kilometers, or 740 acres.[55]

Technology will change. Faster processors will stitch together and georectify images more quickly. The acuity of photographic sensors will improve, as will the endurance and range of drones. Increasing levels of autonomy in both flight software and post-processing software will allow for the creation of cheap maps with increasingly less direct human intervention. However, the basic principles explained in this chapter—how a drone uses a camera to capture an image, how many of those images are combined with one another, and how they are georeferenced—will remain unchanged for the foreseeable future. §

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CHAPTER 5: MAPPING IN PRACTICE

FAINE GREENWOOD

Chad Hill flies a custom-built drone at the Feifa archeeological site in Jordan as part of his research for the "Follow the Pots" project. Image courtesy Morag Kersel/Follow the Pots.

This chapter discusses several pioneering efforts that have been using drones to create community and cadastral maps, among other types. Drones are especially useful for mapping small areas or doing projects that were too minor to be budgeted for in the past. Inexpensive to operate and easy to learn how to use, drones permit organizations and individuals to easily gather aerial data. "You don't have one major government department sitting in the capital city and rotting away because they can't do anything, because the scale of the economy never justified doing any mapping," says Walter Volkmann of Micro Aerial Projects, a drone company based in Florida. "Now you have local capacity."[1]

Indonesian geographer and drone pilot Irendra Radjawali uses unmanned aerial vehicles in his work with the indigenous Dayak people of Borneo. He is training them to use UAVs and to utilize UAV imagery to defend themselves against illegal land use and corporate land-grabbing, a common problem in Southeast Asia.[2] "If you have to sit together with decision-makers at any level, you need more than rhetoric," he explains. "You need arguments, and building arguments needs data first. And that means methods of collecting the data, analyzing the data."

With his assistance, the Dayaks have successfully used UAV imagery to challenge in court a mining company engaged in environmentally damaging activities, a success Radjawali hopes to replicate with his new network of Community Drones schools. "The idea of making the schools," Radjawali says, "is not only to teach them how to make drones, but also to understand what the products of the drones are, how they can understand the maps. The drone is just part of the process."[3]

Gregor MacLennan, the program director for Digital Democracy, a group based in Oakland, Calif., has helped Guyana's Wapishana people use a drone to monitor their ancestral territory. "Our aim beyond the drone work is developing a toolbox of tech that can help different communities address the challenges they're facing with land rights and resources … not just training people to use the drone, but building the community structure necessary to manage something like that, the training required to help people use the images," he says.[4] "There's an awful lot more than just buying the drone."

COMMUNITY MAPPING

Community mapping is a form of participatory mapping that encourages community members to make their own spatial representations of their own land, in a way that makes sense to them. What is to be mapped may cover a wide range of categories, from plots of land to fields of crops to sites of particular spiritual and historical importance. Unlike with top-down mapping, in which authorities decide which space belongs to whom and how space ought to be used, community members make their own assessments in a participatory and cooperative fashion.

In this approach, the involvement of community members in the UAV flight and mapping process is of paramount importance; they will not be able to make very good use of the tool if no one explains to them how it works. The best practitioners in the UAV mapping field make an effort to collect their data in a transparent and open way, explaining their motivations and their intentions as they proceed.

Today's UAV technology, combined with the photogrammetric processing software and computer vision tools that are now widely available, has made this collaborative process among community members, governments, and aid organizations easier than ever before. The Dayaks face regular challenges to their land rights from resource extraction companies, such as bauxite miners and palm oil growers. Radjawali works with the Dayaks via the Swandiri Institute, an Indonesian organization dedicated to researching the political ecology and social impacts of environmental change. Community Drones, the network of schools that Radjawali and the Swandiri Institute have opened, teaches villagers how to document their land holdings, how to gather photographic evidence of illegal use of their land by interlopers, and how to adjudicate community land disputes.

In April 2014, Radjawali used a homemade tricopter UAV to map 30 hectares of land that Dayaks in the West Kalimantan province's Sanggau Regency said had been damaged by a bauxite mine. The UAV was equipped with a Canon PowerShot SX260 camera with a focal length between 4.5 and 25 mm, and was flown autonomously using the APM flight controller and Mission Planner software.

To map 30 hectares, Radjawali flew the UAV at 250 meters above ground level, shooting about 240 photographs at a pixel resolution of 9 cm. The images were processed in the VisualSFM open-source photogrammetry software, which stitched them together into a high-resolution map, a process that took roughly an hour. Radjawali used the Canon SX260's GPS for georeferencing, as well as using his Magellan eXplorist 310 GPS unit to collect ground control points.

The resulting map showed a desert where a small lake used to be; illegal bauxite washing (a step in extracting aluminum from bauxite ore) had depleted the lake's water. The mining activity was conducted outside of a concession area designated for the purpose, another violation. Dayak representatives were able to use the resulting aerial photographs as evidence in a court case against the mining company, which the Dayaks would eventually win, ending the mining operation.[5]

Meanwhile, in Guyana, MacLennan has been working with the Wapishana[6] to monitor a savannah and rainforest territory totaling 7 million acres. MacLennan taught a Wapishana monitoring team how to build two fixed-wing UAVs: one for flight practice and one capable of autonomous flight. They used this second UAV to shoot imagery of the forest and the illegal mining activity that goes on within it. MacLennan has worked with the Wapishana since 2008, helping them create the local monitoring team to build maps to support their ancestral land claim. They currently hold legal title to only about 20 percent of that claim, he says.

The territory claimed by the Wapishana, who number about 7,000 individuals, is mineral-rich and has attracted the attention of wildcat gold miners who cut away the forest and pollute water sources during their excavations. While these activities are illegal, local government authorities often look the other way, preferring to pocket the money the miners give them. Some Wapishana also profit from the mining industry, MacLennan says. They believe that the income it generates outweighs the damage done to the environment.

Beyond the immediate threat of illegal mining, the Wapishana also needed an inexpensive way to make maps of their villages and their holdings, which could be used to negotiate property

Irendra Radjawali

Bauxite mining on the banks of the Kapuas River, which runs through the Indonesian portion of the island of Borneo.

lines, the equal use of resources, and other basic community functions. Satellite imagery was too low in resolution and prone to cloud cover for their needs, so MacLennan and the Wapishana hit upon the idea of using a drone.

MacLennan, new to the UAV world, had intended to build the drone (an FX61 fixed-wing) himself before he arrived in Guyana in the fall of 2014, but he ran out of time. Instead, he built the UAV with the monitoring team, an experience he soon realized was very valuable for everyone involved. "There's a lot of issues with anyone going in and flying a drone over your village. … The fact that it was their drone, that they built themselves, really changed the dynamic," MacLennan says. "Their sense of owning the tech, it being theirs, would have been different if this had been a case of 'We got this great tech from the gringos, and they taught us how to use it.'"

Already accustomed to repairing motorbikes and boat motors, the Wapishana quickly took to drone building, MacLennan says. He worked with them on flight training, and then they began to fly mapping missions, shooting images and video with a GoPro camera. They were able to shoot enough images to create a map, and as of June 2015, MacLennan was working with a trial version of the Pix4D software to process the images into an orthophoto, an aerial photograph geometrically corrected to have a uniform scale, thus making it usable as a map. The monitoring team planned to present the orthophoto at a large Wapishana tribal meeting scheduled for July of 2015.

The initial experiments with the drone, as is often the case with this new technology, did not always go smoothly. Both landing and takeoff with the drone were difficult due to the dense vegetation of the Wapishana's territory. MacLennan hopes to address this problem during his next trip to Guyana at the end of 2015, perhaps by building a fixed-wing plane light enough to crash without being too badly damaged. The UAV's link to the radio control broke just as MacLennan was leaving, and although he managed to get it repaired by the manufacturer and sent back, he had been unable as of June 2015 to connect with his Wapishana colleagues on Skype to walk them through the repair process.

"I see the drone project as an experiment, an amazing new tech which is exciting, but it's not entirely clear how it can be used," MacLennan says. "One way we found very quickly, is that it gets people in the press and funders really excited. But the second part is: What does it actually change on the ground?" MacLennan hopes to start similar Digital Democracy drone-mapping experiments in Peru.

In neighboring Suriname, meanwhile, the GISsat company has used UAVs to create a number of geographic products for indigenous communities there. These include projects to monitor logging, conduct an inventory of housing facilities for village planning, and create orthophoto maps that the village board and local nongovernmental organizations can incorporate into their work. In a presentation about its work at a 2013 conference,[7] GISsat emphasized the importance of working with traditional authorities to get an "entrance pass" into the region, and involving the local community to support ground activities, such as collecting ground control points. Using a Trimble Gatewing X100 fixed-wing UAV, GISsat was able to map 0.95 square kilometers of an indigenous-controlled area, with a total flight time of 38 minutes.

CADASTRAL MAPPING

Cadastral mapping is the spatial representation of cadastre records, which, per a definition by the U.N. Food and Agriculture Organization, are "records showing the extent, value and ownership (or other basis for use or occupancy) of land."[8] Of course, cadastral maps and community maps are not mutually exclusive categories. However, cadastral maps usually must adhere to a government standard of ground resolution and design. UAVs could be used by state authorities to update cadastral maps without community involvement; however, we focus our discussion on cadastral mapping using UAVs in collaboration with local communities.

Cadastral maps are often unavailable or very out of date in the developing world, a situation that often has the worst impact on indigenous and poor people. [9] Without adequate legal proof of land ownership, they are vulnerable to having their land "grabbed," to seeing the natural resources they rely on exploited by outside players without adequate remuneration, and to becoming embroiled in confusing property disputes.

The Land Alliance, a nonprofit dedicated to the study of land issues, has recently begun experimenting with UAVs for cadastral mapping in Peru, where many thousands of people lack land title.[10] It emphasizes an approach in which government policy is linked to geospatial data and community participation, using the UAV's ability to quickly gather aerial information to permit a more real-time mapping process. Landowners are actively involved in planning, marking the boundaries of land parcels so that they are visible from the air, and reviewing and verifying the resulting information. Per the Land Alliance,[11] regional government representatives are also intimately involved in the process, helping to resolve disputes and mediate the process.

Walter Volkmann of Micro Aerial Projects recently completed a World Bank-funded mapping project in Albania, one of the least developed countries in Europe.[12] After the People's Socialist Republic of Albania was officially dissolved in 1992 after parliamentary elections, the country embarked on a large-scale property privatization effort. Many observers considered this effort to be corrupt and largely for the benefit of people with political connections—the privatization efforts were carried out with inadequate access to information and with a lack of transparency.[13]

Albania introduced a computerized land administration system in 2012, based on international standards, but only 20 percent of the nation's properties are currently covered in the database, while almost 80 percent are covered only by paper maps that are of insufficient quality to be used in the database. Volkmann's project was intended as a pilot test of a UAV-based method of cadastral mapping that could be used both to support land registration efforts and to improve geospatial data that already existed.

While there are existing high-resolution orthophotos of Albania, covering the entire country, the imagery dates from 2007. Lower-resolution imagery from Google Earth, which dates to 2012, is inadequate for the task of identifying and defining property boundaries, as is required in a cadastral survey. The UAV was able to fill this coverage gap, generating high-resolution, up-to-date imagery that could be used immediately. Volkmann and his colleagues tested their UAV mapping system in three locations: an agricultural area called Fushe Milot, a dense urban area known as Komuna Farke, and a strip of the Elbasan national highway, all in the general vicinity of Tirana, Albania's capital. The Elbasan highway site and the Fushe Milot site were chosen as examples of how UAV imagery can provide useful information for infrastructure development and management. Plans for a new highway and a new water pipeline would route them through areas where land ownership is unclear—an information deficit the drone-mapping project was meant to help close.

The team used a custom-built UAV equipped with a Samsung NX1000 camera and 16mm lens, with the intent of keeping costs low and thus accessible to residents of a developing country. They flew their mapping UAV 75 meters above the ground at the Fushe Milot and Elbasan highway sites, and at 50 meters at the urban test site at Komuna Farke. The flights were designed so there would be 80 percent forward overlap and 70 percent side overlap of images, which resulted in large data sets and long processing times.

The mapping process itself did not take the team very long. In Volkmann's report for the World Bank, he said it took a total of three hours to carry out field surveying for the Fushe Milot site, greatly reduced from the three to four weeks such a survey would have taken in the past. To cover 23 hectares at the Fushe Milot site with a ground sampling distance (GSD) of 1.8 cm, the UAV required four flights of about 10 minutes in length.

However, processing the data took many hours, Volkmann reported, and it proved to be the limiting factor of the exercise. It took 48 hours for Volkmann to produce a 1.8 cm-resolution digital orthophoto of the Fushe Milot site using Agisoft PhotoScan software, with a positional accuracy of under 10 cm. A week after the aerial survey, the team was able to show this orthophoto to local landowners, who were asked to define the boundaries of their property.

This process was a success: "In approximately 3 hours we were able to define the boundaries of 29 property parcels on the orthophoto," Volkmann wrote.[14] The UAV maps were overlaid onto scanned images of the existing and out-of-date paper registration index maps, which made the differences between the two clearly visible.

ENVIRONMENTAL & CONSERVATION MAPPING

UAV technology is already finding wide adoption among scientists and conservationists around the world, who have embraced its low cost and relative ease of use. Such efforts are discussed in detail in Chapter 7.

ARCHAEOLOGICAL MAPPING

Archaeologists have been early adopters of UAV technology, embracing it as an easy-to-use and inexpensive alternative to the pricey manned aerial surveys and often cloud-obscured satellite data they used to rely on. Archaeological researchers currently use UAVs for initial surveys of areas with suspected historical sites, georeferenced 3D mapping, aerial thermography, and site monitoring, among other applications. The Digital Archaeological Record[15] has an excellent collection of papers describing archaeological UAV use cases, some of which we will describe here.

UAVs show potential in the arena of architectural cultural heritage reconstruction, making it easier to make digital "copies" of important buildings and sites[16]—data that will virtually preserve them if these irreplaceable historic sites are destroyed or damaged in the future. Archaeologists in Peru, as described in Chapter 9, have begun using UAVs to produce detailed 3D images of historical sites around the country. These can then be stored in a database and used for further research, as well as to assess the risk of damage or destruction involving places particularly at risk.

Today's inexpensive and programmable UAVs have made aerial thermography, the practice of using thermal cameras to detect hidden archaeological sites, considerably easier than it was in the past. While researchers have experimented with thermal imagery collected from manned aircraft, kites, and even a manned powered parachute, the use of UAVs has become more attractive because of their precision and ability to fly in relatively rough conditions. This was demonstrated by a 2013 study in New Mexico[17] carried out by researchers from the University of Arkansas and the University of North Florida.

The researchers used a CineStar 8 UAV equipped with a FLIR thermal camera to search for surface and subsurface cultural remains at an archaeological site known as Blue J, in northwestern New Mexico near the famous Chaco Canyon. The ancestral Pueblo site consists of around 60 households spread over 2 square kilometers. It has been thoroughly covered with deposits of sand and dirt, making it difficult for archaeologists to detect where other structures might have been when the site was occupied. Thermal cameras are able to discriminate between different materials due to the different ways they interact with thermal infrared radiation at different times of day, and can produce images that show the location of structures invisible or almost invisible to the naked eye. Thermal cameras like the FLIR Tau 2 LWIR that the researchers used have become small enough to be mounted on a drone capable of carrying a reasonably heavy payload, such as the eight-armed CineStar, which can lift 4.4 pounds.


A three-dimensional map of Antiochia ad Cragum, a research site in the village of Güney on Turkey's south coast.

Using CineStar's proprietary mission-planning software, the archaeologists flew five surveys at the site, with an average flight time of 11 minutes from takeoff to touchdown. The researchers used Agisoft PhotoScan software to create both color and thermal ortho-imagery, which was georeferenced using ground control points taken at the site.

The researchers found that the thermal imagery showed almost all of the archaeological features discovered previously by a more traditional ground survey, as well as a number of features that had not been detected before. In their conclusion, the archaeologists wrote that the UAV "offers a means to collect and process thermal imagery over very large areas extremely rapidly, which is perhaps its greatest advantage."[18]

Archaeologists Austin "Chad" Hill and Dr. Morag Kersel of the interdisciplinary "Follow the Pots" project[19] are using UAVs to monitor looting at the Early Bronze Age sites of Bab adh-Dhra`, en-Naqa, and Fifa in Jordan. The UAV flights are part of a planned five-year study of how people loot, sell, and collect pottery from the estimated nearly 10,000 graves in the area, which have been looted for decades.[20]

Hill and Kersel hope their research will allow them to literally "follow the pots" from where they were initially collected, tracing the artifacts' journey from looters to middlemen to dealers, all the way to the final buyer. They also hope that their multi-year project will help assess government and police efforts to protect the sites, as well as the efficiency of local outreach programs, guards, fences, and other efforts to end the looting. UAV imagery has given them a low-cost way of documenting changes at the sites on a yearly basis.

Kersel, an assistant professor at DePaul University, and Hill, a researcher at the University of Connecticut, have used both multi-rotor UAVs and a fixed-wing UAV to gather three-dimensional aerial imagery, which they have collected since 2013 at approximately the same time each year.

BEN KREIMER

The UAV project came about after the researchers had experienced trouble obtaining adequate aerial imagery of their study sites, finding that each manned flight would cost them as much as $2,000.[21] Kersel and Hill realized that UAVs could bring down their costs and allow them to conduct aerial surveys as often as they wanted to, and Hill—a childhood RC enthusiast—began to build a mapping platform, keeping the costs down and allowing him to fix the aircraft himself if needed.

The UAVs, Hill explained in an interview, are used to gather high-resolution 3D data of the Bronze Age sites once a year, which is then properly georeferenced and processed with a GIS system. The researchers look for signs of new looting at the sites, which can be easily compared with the information gathered from previous years.

"With the difference analysis of GIS data, we can analyze how the shape of the land has changed from year to year with a high degree of accuracy—with the looting events at the site, with negative change where ditches have been dug, where the soil has been thrown up around the new pit," Hill explains.

When in the field, Hill walks below the UAV while carrying a Nexus7 tablet running the DroidPlanner autonomous flight-planning software, enabling him to keep the drone within his line of sight at all times. Hill tends to fly his UAVs at about 60 meters off the ground, with the Skywalker FPV plane typically flying for 25 to 30 minutes.

The researchers use the onboard GPS from a Canon S100 camera for initial georeferencing, then use precisely surveyed Total Station GPS ground control points to georeference the aerial data with Agisoft PhotoScan Pro.

Hill is a believer in his DIY drone solution: "It's better to buy lower-end stuff that you expect to have problems with, because you'll have problems with any equipment," he explains. Since the UAV project began in 2013, Hill says, the high-resolution and three-dimensional imagery gathered by the UAVs has enabled the researchers to document 37 new looting pits. "We've been able to document changes in the site we wouldn't have been able to detect with a satellite," he says.

GEOMORPHOLOGICAL MAPPING

Geologists also have begun using drones to make maps. Geomorphological maps are maps that describe terrain based on its geological features.[22] Christopher Hackney and Alexander Clayton of the University of Southampton in England used a small Quest 200 fixed-wing UAV to map a series of moraines in the foreland* of Skaftafellsjokull, a glacier in Iceland. They are seeking to understand how the geological features have been shaped by the climate. "These features are located in a topographically constrained region which does not easily facilitate high resolution mapping with terrestrial laser scanning, Lidar or satellite radar mapping,"[23] they wrote. Hackney and Clayton discuss other geological drone mapping efforts to monitor soil erosion in Morocco, landslides in the French Alps, gully evolution in South African grasslands, and Fountain Glacier in Canada.[24]

* The foreland of a glacier is the area immediately in front of the ice's current extent.

Hackney and Clayton mention that some UAVs have been equipped with LIDAR— a remote sensing technology using lasers to measure altitude†—but that "the current suite of LIDAR sensors which may be deployed on UAVs are less high powered than traditional LIDARS and have a higher signal-to-noise ratio."[25] They speculate that LIDAR may in the future enable greater surface detail to be obtained than at present, but for now they recommend photogrammetric techniques that create 3D models from overlapping camera images, like those described in the previous chapter.

CONCLUSION

This description of drone mapping efforts is naturally not exhaustive. Indeed, given the rapid growth in drone use, no exhaustive listing is possible. Nevertheless, for a diversity of examples beyond those described in this chapter, consult a database that New America is continually updating, available online at: drones.newamerica.org. §

† LIDAR measures the distance from the drone to features on the ground; if the absolute position of the drone is known from GPS measurements, the LIDAR thus measures the altitude of ground features.

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CHAPTER 6: UAVS AND HUMANITARIAN RESPONSE

PATRICK MEIER

The first high-resolution aerial image of a major disaster was a black and white photograph of San Francisco in ruins after the devastating earthquake of 1906. A large 49-pound camera attached to a set of kites captured the damaged city from 112,000 feet in the air. The photographer, George Lawrence, sold prints of his aerial image of the city to intrigued individuals for $125 apiece, netting him close to $400,000 in sales (in 2015 dollars).[1] Other early users of aerial imagery in disaster situations included the military. In 1923, the U.S. Air Force took aerial photographs of the Honda Point disaster in California after seven large ships ran aground during a foggy night.[2] Over the course of World War I and World War II, militaries around the world made strides in the use of manned aircraft to capture aerial imagery for reconnaissance purposes. At times, this included assessing disaster damage following air raids such as those carried out on Berlin in 1945. Additional examples of aerial imagery use over the past century relate to major mining and industrial disasters, including Chernobyl in 1986. Aerial imagery was also used in the wake of Hurricane Mitch in 1998. More recently, unmanned aerial vehicles (UAVs) were used to capture aerial imagery following the 2010 Haiti earthquake,[3] while manned aircraft captured imagery after Hurricane Sandy in 2012 for damage assessment.

Aerial imagery of disaster-affected areas is still in great demand today. Indeed, national and international humanitarian organizations are increasingly turning to aerial imagery captured by UAVs to assess infrastructure damage and resulting needs after major disasters. UAVs provide a number of advantages over manned aircraft and satellites. Manned aircraft cannot be programmed to follow designated routes that require very precise flight paths and tight turns, for example. In addition, manned aircraft are typically more expensive to operate and maintain than small UAVs and tend to require a lot more infrastructure, such as runways. Compared to satellite imagery, aerial imagery from UAVs is available at considerably higher spatial resolutions. The most sophisticated commercial satellite available today offers imagery at a resolution of 31 centimeters,[4] while aerial imagery can generate sub 1-centimeter resolution. UAVs can also capture high-resolution oblique imagery by positioning cameras at an angle—say, 45 degrees—rather than straight down, which is known as nadir imagery. This enables the creation of very high-resolution 3D models.[5] UAVs, unlike satellites, can operate below cloud cover. Lastly, while just a handful of multibillion-dollar companies can own and operate satellites, international humanitarian groups, national disaster management organizations, and local communities can own and operate UAVs themselves.

Over the past several years, UAVs have been used in response to, among other natural disasters: the Nepal earthquakes (2015), Cyclone Pam in Vanuatu (2015), Typhoon Ruby in the

This photograph of San Francisco was taken by George Lawrence 6 weeks after the 1906 earthquake. (Image from Wikimedia Commons.)

Philippines (2014), the China earthquake (2014), Cyclone Ita in the Solomon Islands (2014), flooding in Bosnia and Herzegovina (2014), Typhoon Haiyan in the Philippines (2013), and Hurricane Sandy in New York (2012).[6] This chapter provides an introduction to the use of UAVs for humanitarian response by outlining the opportunities and challenges presented by this new technology.

HUMANITARIAN UAVS

UAVs have relevance across the entire disaster cycle—from risk reduction to preparedness, response, search and rescue, recovery, and reconstruction. This chapter focuses specifically on post-disaster applications of UAVs.* As evidenced by recent humanitarian efforts in Nepal and Vanuatu, UAVs are increasingly used to support traditional damage and needs assessments. Indeed, humanitarian groups are turning to aerial surveys to complement or accelerate their traditional field-based damage and needs assessment surveys. These damage assessments typically include buildings (such as dwellings, schools, and hospitals) and transportation infrastructure (roads, bridges, etc.). Field-based surveys are time-consuming, often taking weeks to complete. Questionnaires, like the United Nations' Multi-cluster Initial Rapid Assessment (MIRA) and the World Bank's Post Disaster Needs Assessment (PDNA), include dozens of questions to guide the on-the-ground assessment of disaster damage and ensuing needs.[7] In addition to being time-consuming, field surveys suffer from data quality issues; individuals filling out these questionnaires may interpret the questions differently or overlook important questions.[8] Aerial surveys can accelerate the damage assessment process by prioritizing those areas that require field surveys, while also serving as an important quality control mechanism to triangulate and complement field-based surveys.

Oblique imagery is considered more useful for disaster damage assessment purposes than nadir imagery, since the angle provides the necessary perspective to assess whether the walls of buildings are damaged. That said, unlike nadir imagery, oblique images cannot easily be "orthorectified"[9]—that is, be corrected so points on the picture correctly correspond to points in the real world that can be tagged by GPS. This currently limits the analysis of oblique imagery to purely manual methods when integrating the results with other GIS (geographic information system) data.

* Humanitarian organizations do not typically take on the responsibility of search and rescue (SAR) efforts, which are primarily carried out by the military or other dedicated SAR teams. See box on page 59 on search and rescue.

Medair and DroneAdventures

This mosaic of photographs taken from a drone shows an area in the Philippines damaged during Typhoon Haiyan/Yolanda in 2013, a few months after the storm. It was one of the strongest storms ever recorded; it killed over 6,000 people in the Philippines alone.

Using oblique images to interpret disaster damage in nadir images is thus a useful method. Another approach is to create high-resolution 3D models from nadir and oblique imagery. These models—also referred to as "point clouds"—can be produced using standard software packages. Point clouds provide analysts with a full surround-view, fly-through model of an affected area. 3D models thus have an obvious advantage over standard nadir and oblique images, since the latter are limited by a fixed perspective.

Aerial videos can also provide important insights on disaster damage, though they are often time-consuming to analyze. Moreover, as in oblique images, features in aerial videos cannot be easily georeferenced. Nevertheless, aerial videos have been used to provide additional situational awareness for particularly dense urban areas affected by disasters, for instance after Cyclone Pam in Vanuatu in March, 2015.

Other common applications of UAVs include road-clearance operations and logistics support. Aerial imagery can help humanitarians identify which roads are blocked by debris and which may still be passable. In addition, UAVs can be used to identify locations for setting up a humanitarian base of operations and areas in which displaced populations can be relocated. Other uses include identifying displaced populations, estimating population numbers, and locating remains of the deceased. Non-operational applications for aerial imagery include advocacy, awareness-raising, and public communications.

UAVs can also be used to carry small payloads and to provide communication services (3G/4G, WiFi), but these uses go beyond the scope of this chapter. Humanitarian organizations such as the U.N. World Health Organization and Médecins Sans Frontières (MSF) are testing the use of UAVs to transport lightweight medical payloads like vaccines and medication across some 30 to 50 kilometers.[10] This is a particularly promising use from a technology and logistics perspective, which is why Amazon, Google, DHL, and others are actively pursuing drone delivery. The Emergency Telecommunications Cluster (ETC), an international network of organizations, is also exploring the use of UAVs for communication services. While the ETC's experts suggest this use of UAVs won't mature as quickly as other applications, companies such as Google and Facebook are investing millions of dollars to provide aerial connectivity solutions.

THE SEARCHERS

Search and rescue specialists are beginning to experiment with using drones as a complement to older techniques: helicopters, dog teams, and on-foot sweeps. Drones have already been used to make some notable finds, but the technology has yet to be adopted widely, due to both technological and regulatory barriers.

Perhaps the first search-and-rescue find made with a UAV took place in May 2013, when Canadian Mounties in Saskatchewan province used a Draganflyer X4-ES drone to find a man whose car had flipped over in the snow.[*] A ground search and a helicopter sweep both failed to find the young car-crash victim, but the drone, equipped with an infrared camera, managed to detect his heat signature. In a separate incident, in July 2014, David Lesh used his drone to find 82-year-old Guillermo DeVenecia in a Wisconsin bean field. The old man had been missing for three days.[†]

Texas EquuSearch began as a mounted search and rescue team, but founder Tim Miller says that his group has used its drones to recover the remains of 11 people since 2005.[‡] In April 2015, a Maine search-and-rescue organization became the first civilian entity to receive official Federal Aviation Administration permission to use drones in its operations.[§] In December 2013, Jim Bowers founded a volunteer group in California that uses drones in search and rescue. Bowers' group, called SWARM, now has members in 31 countries.[¶]

Ben McCandless of the Appalachian Search and Rescue Conference, a volunteer group, says UAV's short battery life limits their capability, along with constraints in visual and infrared sensor quality.[**] Few protocols exist to ensure the safety of human searchers while UAVs are flying overhead, he notes. McCandless speculates that the development of such protocols, and effective techniques more generally, is hampered because some search and rescue professionals who use drones are skittish of running afoul of regulators, and so do not discuss their efforts. It seems clear that as technology improves and regulations liberalize, drones will become only more useful in searches for missing people, in the wild, and after accidents and natural disasters.

-Faine Greenwood

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VANUATU AND CYCLONE PAM

In March 2015, a Category 5 cyclone devastated the islands of Vanuatu. The World Bank activated the Humanitarian UAV Network (UAViators.org) to carry out aerial surveys that would complement the bank's field-based disaster damage assessments of buildings.[11] UAViators identified two professional UAV teams in the region, which were subsequently contracted by the bank for the mission. The UAV teams used multi-rotor UAVs (hexacopters and quadcopters) to survey about 10 percent of the affected areas. Both nadir and oblique images were collected at approximately 5-centimeter resolution. Aerial videos were also captured. The nadir and oblique images were subsequently analyzed using a three-tiered scale provided by the bank: completely destroyed, partially damaged (i.e., repairable), and largely intact. Orthorectified mosaics drawn from the nadir images were first analyzed by Humanitarian OpenStreetMap, a group of crowd-sourced volunteers. MicroMappers, another such group, analyzed some 2,000 oblique images. The resulting analysis was used to complement the field-based surveys. 3D models were not used to carry out more in-depth assessments because the World Bank was not initially aware that 3D models were an option.

The success of this UAV mission was largely the result of collaboration among the World Bank, UAV teams, the government of Vanuatu, air traffic control, and the Australian Defense Force (ADF). The government gave the teams permission to fly using Extended Line of Site, which meant the UAVs could cover more ground. In addition, thanks to the strong collaboration between air traffic control and the ADF, the UAV teams were able to operate safely near the international airport despite the presence of commercial and military aircraft in the vicinity.

The most pressing challenges related to weather, logistics, connectivity, and data formatting. On logistics, moving across the main island and accessing outlying islands proved particularly difficult due to the terrain and the lack of reliable transportation (both marine and aerial) to the outer islands. Limited Internet connectivity also added significant delays—often days—since it took a lot of time to upload the large files of aerial imagery to the Web. Finally, the lack of consistent labeling of the aerial data caused further delays, since no one in Vanuatu was tasked with this job. The resulting data was thus difficult to access and make sense of.

NEPAL EARTHQUAKES

An unprecedented number of UAVs were used in response to the devastating Nepal earthquakes in April and May 2015. The U.N. Office for the Coordination of Humanitarian Affairs (OCHA) publicly encouraged UAV teams to check in with the Humanitarian UAV Network (UAViators) for the purposes of coordination and safety. A total of 15 UAV teams liaised with UAViators, as did a number of humanitarian organizations including OCHA, UNICEF, UNESCO, the World Bank, and the International Medical Corps.[12] The latter requested aerial imagery of specific sites for a variety of reasons, ranging from disaster damage assessment to population displacement. The majority of UAV assets used in Nepal were multi-rotors.

The lack of UAV regulations in Nepal posed a number of challenges. Some UAV teams chose to assume that the lack of regulations meant they could operate as they wished without seeking permission. This backfired. Several teams were arrested by the police and over a dozen UAVs were confiscated.* Within a week of the first earthquake, the government of Nepal significantly limited the use of UAVs to those efforts that clearly had an official humanitarian purpose. In other words, "drone journalists" were in effect banned from operating. The process to request official permission was unclear, however. UAV teams had to request two separate permissions, one from the Civil Aviation Authority for operating UAVs and one from the Ministry of Information and Communications to capture pictures and videos from UAVs.

As a result of these constraints and uncertainties, the most active UAV teams partnered directly with the Nepalese military, police, and other authorities. These UAV teams shared their imagery exclusively with the government entities and not with international humanitarian organizations. Besides the lack of regulations, other major challenges included limited Internet connectivity, difficulty in accessing rural areas, and the lack of long-range, fixed-wing UAVs.

BEST PRACTICES

Using UAVs for disaster response is very different from using them for journalism, crop management, or real estate marketing. While this should be obvious, the main reason that mistakes are made with UAVs in humanitarian settings is because those drone operators have little or no

* In part to prevent such incidents, the UAViators code of conduct (online at http://uaviators.org/docs) recommends always seeking permission of local authorities.

Building fixed-wing drones with a team in the Philippines.

SKYEYE


Oblique imagery taken from a drone used in damage assessment

Patrick Meier

background in disaster response. Meanwhile, seasoned humanitarians using UAVs for the first time may assume that they know what they're doing because they have years of experience in disaster management. This shortsighted logic can have dramatic ramifications for those legitimate and experienced UAV teams who are working directly with established humanitarian organizations to support their relief efforts. In the case of the 2015 Nepal earthquakes, the above logic, coupled with the presence of "drone journalists," was in part responsible for the government's decision to heavily limit the use of UAVs post-disaster.

What follows is a summary of some of the most important guidelines drawn from the Humanitarian UAV Network's Code of Conduct and Best Practices documents.[13] As such, it is not comprehensive and should be viewed as a minimum set of guidelines to ensure the safe, coordinated, and effective use of UAVs in disaster response.

UAVs are not always the most appropriate technology to use for the humanitarian tasks at hand. If they are, then UAV operators should be sure to select the appropriate UAV model for the mission and that they identify an appropriate spatial resolution for the imagery collected. They must keep in mind that there is a trade-off between resolution and how much surface area a UAV can cover. Second, UAV operations should stay legal at all times. UAV operators should research the regulations in the country of interest. If no regulations exist for the country in question, this does not mean operators have the right to operate UAV(s) as they like. Even when clear regulations do exist, it is the operator's responsibility to check in with the country's civil aviation authority or aviation ministry to ensure they have all the required permits. If operators are not able to contact these institutions, they should be sure to approach local government authorities such as a mayor's office and local police to request permission.

Once a UAV team has been granted official permission to operate, this does not mean they can ignore the local communities they fly over. It is particularly important to engage local communities and involve them in UAV missions. UAV teams must take the necessary time to explain what they want to do and why. They must clearly demonstrate the added value that their UAV missions are expected to yield and let communities know who will have access to the resulting imagery, how, and for what purpose.

If operating in a complex airspace—one with passenger aircraft, commercial airplanes, humanitarian cargo aircraft, or search and rescue helicopters—then operators will need to liaise directly with the military and the closest air traffic control tower.

UAViators actively promotes the sharing of aerial imagery during disasters in order to inform relief efforts. The network suggests using the Creative Commons CC BY data-sharing license. This license requires that imagery be attributed to the person or organization that gathered it and enables humanitarian groups to integrate data derived from that imagery into other data sets for disaster assessment and decision-making purposes.

Note that data sharing typically entails pushing imagery to the Web. This can be particularly challenging in disaster zones, since cellphone towers and other communications infrastructure may have been damaged. Aerial imagery can often run into gigabytes worth of data. Uploading this data when there is limited or spotty Internet connectivity can significantly slow down if not entirely halt humanitarian UAV missions. Humanitarian drone operators should be sure to plan for the additional technology they'll need to bring if you expect to face connectivity issues. They should determine earlier rather than later which format and labeling standard will be used to share the imagery with partners.

Humanitarian UAV missions do not end when the UAVs land. The main purpose of using UAVs in disaster response is to collect data to accelerate and improve timely decision-making. This requires that the collected data be processed and analyzed, and that the results are shared with appropriate end users. Aid and development organizations typically use their own damage assessment methods to classify structures as destroyed versus damaged versus largely intact. GIS and imagery analysts within these organizations tend to carry out this classification process manually. Platforms such as Humanitarian OpenStreetMap and MicroMappers have also experimented with crowd-sourcing to analyze disaster damage in nadir and oblique aerial imagery.[14]

In alleviating suffering after a natural disaster, time is of the essence. The speed with which UAVs can gather data about affected areas makes them an important tool in disaster response. As the technology matures, the uses of unmanned aircraft in the aftermath of natural disasters will only increase. §

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CHAPTER 7: DRONES AND CONSERVATION

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An acacia tree in the Kenyan savannah.

There are fewer different kinds of plants and animals in the world today than in the recent past,[1] in large part because of hunting[2] and land-cover change.[3] Hunting by people has been leading to species extinctions since prehistoric times.[4] The threat of extinctions is growing worse; at present it is estimated that one-fifth of the world's extant vertebrate species are threatened.[5] In tropical regions, vast areas of forest are being converted to agricultural purposes, decreasing biodiversity.[6]

Conservation workers are therefore in need of tools that allow them to frequently monitor wildlife populations to determine trends, to monitor land-cover change (as specialists refer to deforestation and similar phenomena), and to detect threats such as poachers.

Currently, wildlife monitoring is commonly conducted on foot, by car, by ship, and by manned plane.[7] Although these methods are well-developed and yield good data, they are expensive and time-consuming. This means they aren't done often, which makes proper statistical trend analyses difficult. For example, a recent survey of the range of the Sumatran orangutan (*Pongo abelii*) took three years to complete at a total cost of $250,000. The survey involved three ground teams that were often deployed to the field at the same time. Due to large mountainous or peat swamp areas that needed to be surveyed, teams sometimes had to walk for several days just to reach the survey location, which made data-gathering a slow and costly process. Conducting such surveys at sufficiently short intervals for trend analyses is not realistic.

The most common approach to classifying land-cover types, and detecting and monitoring changes in land cover, is to use satellite imagery and data.[8] Low- and medium-resolution satellite images are freely available—for example, Landsat (landsat.gsfc.nasa.gov) and MODIS (modis.gsfc.nasa.gov)—but the low resolution (greater than 900 square meters per pixel) makes it difficult to detect small-scale change or to differentiate between similar land-cover types (e.g., young versus mature oil palm plantations or low-impact logged forest versus primary forest).[9] High-resolution satellites, such as QuickBird (digitalglobe.com) and IKONOS (geoeye.com), are better. Pixels as small as a tenth of a square meter make it possible to detect some such changes. However, these images are expensive, at over $10 per square kilometer.[10] Tropical areas are often cloudy. This poses difficulty for frequent monitoring of land-cover change because satellite imagery cannot be obtained at regular intervals.[11]

Even in places where forests are not being cut down, hunting—unsustainable and illegal (hereafter referred to as poaching)—has led to declines in wildlife populations or even extinctions.[12] The poaching threat to wildlife is highlighted by declines in tigers, rhinoceros, and elephants across Africa and Asia.[13] Especially for rhinos in Africa, poaching has reached levels that are endangering populations.

For all three applications—wildlife monitoring, land-cover classification and monitoring, and anti-poaching efforts—drones can help. In the past 15 years, drones have become cheaper and more widely available; in the past few years in particular, many studies have used drones for conservation purposes.[14] This chapter reviews such studies and discusses the limits and future potential of drones for conservation.

Rhinoceros in Nepal and orangutan nests in Sumatra, Indonesia.

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WILDLIFE SURVEYS

In general, the aim of wildlife surveys using drones is to determine the distribution and density of species, which is important baseline information for conservation. Drones have been used to study a wide variety of terrestrial and aquatic species.

In relatively open African savannah-woodland areas, researchers have used drones to count large terrestrial animals such as the black rhinoceros (*Diceros bicornis*), the white rhinoceros (*Ceratotherium simum*),[15] and elephants (*Loxodonta africana*).[16] These studies indicate that rhinos and elephants can be counted well with standard RGB cameras, but that for elephants, drone survey costs might not be competitive with manned aircraft at present due to the limited flight times (around 45 minutes) of systems available for such surveys.[17]

Several bird species—Canada geese (*Branta canadensis)*, snow geese (*Chen caerulescens)*, black-headed gull (*Chroicocephalus ridibundus)*, and white ibis (*Eudocimus albus)*[18]—have been studied with drones as well. Surveys that aim to count birds on the ground need to consider that the drone may disturb the birds, leading them to fly up from the ground and potentially creating a collision risk with the survey drone.[19]

In addition to directly detecting individual animals, researchers have used drones to see and count signs of animal life. These can range from small mounds made by gophers (*Thomomys talpoides*) and ground squirrels (*Ictidomys tridecemlineatus*)[20] to large nests made by Sumatran orangutans[21] and chimpanzees (*Pan troglodytes)*[22].

As all great apes do, orangutans make a new night nest almost every day. The number of nests in an area is often used to determine the animals' presence. This is often favored over direct sightings, because the low densities of orangutan populations mean that survey efforts would have to be very large to detect the orangutans themselves. Recent drone surveys have established that nests can be detected on photos taken from a camera on a drone. Such surveys are now being used to determine the presence of orangutans not only in rainforest areas, but also in areas that have been logged previously and are now being reforested. In such areas, the relative density of nests found during ground surveys correlates well with findings from aerial surveys, which means that using drones to determine the distribution and relative density of orangutans appears promising.

Drones have been used to study animals of different sizes in various aquatic habitats. Smaller fish like salmon have been studied during the annual salmon run in southern British Columbia.[23] The aim of the study was to obtain a high-resolution orthomosaic from drone images to identify individual salmon. The researchers managed to obtain images that gave them a new perspective on how salmon were distributed in the river and allowed them to identify spawning areas. Studies have also investigated the distribution of larger species such as the dugong,[24] the Florida manatee (*Trichechus manatus*), and the American alligator (*Alligator mississippiensis*).[25] Such studies now open up new opportunities to survey species over large areas from the air at potentially lower cost than traditional survey methods, with less disturbance to the studied species. Drones have even been used in cold and challenging environments to detect harp and hooded seals (*Pagophilus groenlandicus* and *Cystophora cristata*).[26] The aim of the seal studies was to assess the feasibility of drones for surveys of seal whelping areas that could potentially replace the costly manned aerial surveys of the West Ice area of the Greenland Sea. The results showed that both adult seals and pups could easily be identified on the images but that long-range drones that can land on ice are needed for these surveys.

DRONE PLATFORMS

Drone surveys for conservation have used both multi-rotor and fixed-wing systems. The choice usually depends on the size of the area to be covered, the detail to be obtained, and the availability of landing areas. For example, it is easier to fly a multi-rotor drone at low altitude compared to a fixed-wing craft, and the low speed of multi-rotors means that motion blur on images is not an issue. Also, the VTOL (vertical takeoff and landing) capability of multi-rotors makes them very suitable when only small areas are available for starting and ending flights.

A large variety of systems have been used, from low-cost do-it-yourself aircraft with limited flight time (60 to 90 minutes) and payload capability[27] to high-end systems able to fly for up to 24 hours and carry heavier payloads, such as the ScanEagle.[28] Fixed-wing drones range in cost from less than $1,000 for a DIY setup that can easily be operated by two people with a simple control system to hundreds of thousands or millions of dollars for high-end systems operated by a team of people with complex and large control arrangements. Multi-rotor systems also range from those with flight durations of about 10 minutes that are available for less than $1,000 and are ready to fly out of the box to systems that cost several tens of thousands of dollars and come with longer flight durations and the capability to carry heavier payloads.

The choice of system is often a trade-off between what is needed and what the costs are, given the available budget. Many conservationists would benefit from systems with a long (multiple-hour) flight duration, but at present the costs often exceed the available funding. Thus there seems to be a relatively large number of conservationists and scientists using systems that cost below $20,000.

COMPARING DRONE SURVEYS TO TRADITIONAL SURVEYS

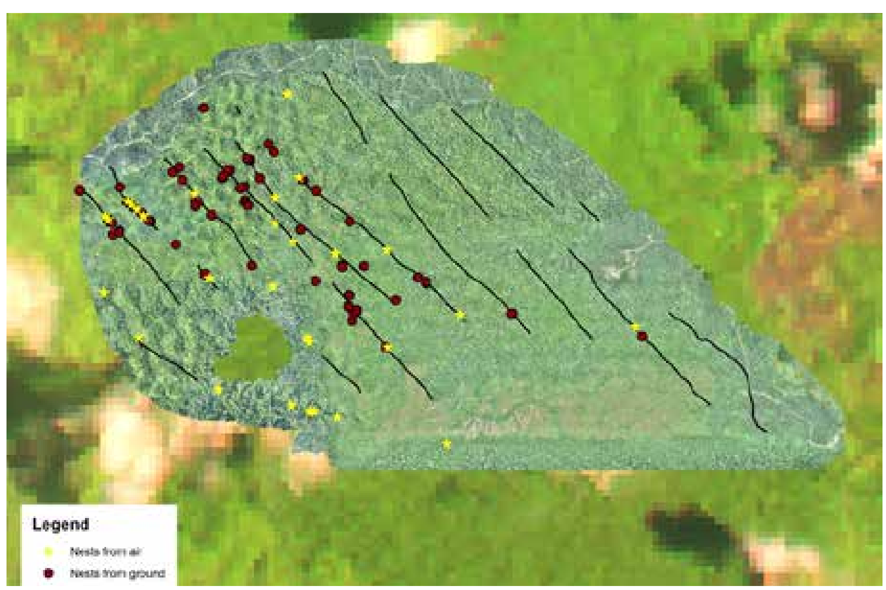
If drones are to ever replace traditional surveying methods, then wildlife counts obtained from drones must be validated against on-the-ground surveys and manned aircraft surveys. The comparison to manned aircraft is important, because during manned flights, data is typically collected by observers who look out the windows and count, rather than by digital cameras, although manned aircraft could in principle carry such cameras.

Ensuring that data are comparable is necessary to be able to determine distribution and density from drone-based data. A mixture of methods using both real and model* animals has been used to assess the detectability of animals from drones. These studies, in both the terrestrial and aquatic realms, have shown that counts based on photo or video data compare well with those achieved during traditional surveys in which humans make direct observations.

These studies also show that factors such as sea conditions[29] or the height of chimpanzee nests in trees, influence detectability.[30] There are limits to the applicability of aerial surveys. Most of the wildlife surveys so far have been conducted to determine where animals live. There has been less effort on deriving density—just how many animals there are—from this data. For animals that can be detected directly, obtaining density can be fairly straightforward if the detection probability is similar throughout the image or in a defined part of it. This can potentially lead to better estimates from aerial drone surveys than from a manned aircraft, where observers are biased toward seeing animals closer to the flight path. In those cases, a detection probability function needs to be fitted on the data that compensates for the decreasing probability of visual detection with distance.[31] For indirect signs, such as great ape nests, not everything observed from the ground is detected on aerial imagery. Although ecologists already have a track history of correction factors to be applied to manned aircraft data, more studies are needed to figure out what analogous correction factors are needed for data derived from drones.

SENSORS

Studies aimed at detecting wildlife have relied almost exclusively on standard RGB cameras. In some cases, thermal-imaging cameras mounted on drones or on telescopic boom lifts, which simulate drone heights, have been used to successfully detect animals.[32] Animal counts from drones are not restricted to wildlife. A drone-mounted thermal camera was used to count cattle at a concentrated feeding operation.[33] This study was aimed at testing how well thermal-imaging cameras could be used to detect large mammals, and the results showed that individual cows could be identified on images that were obtained from a multi-rotor system flying at 100 meters above ground level.



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Transects of drone flights can be seen in this image, as can the location of primate nests.

* For instance, kayaks instead of sea mammals.

COMPUTER VISION AND WILDLIFE SURVEYS

In most wildlife surveys, images from drone flights are processed manually for detecting and counting species.[34] This can, however, be time-consuming and costly with the large number of images and hours of video that are collected by drones. Researchers have therefore been exploring methods to use computer vision algorithms to automatically detect animals or their signs, such as orangutan nests.[35] A main task of such algorithms is to differentiate the object of interest (the animal or nest) from the background. An important consideration is whether object detection needs to occur on the drone itself or can be done on a computer once the data has been transferred from the drone. If the weight limit for an onboard computer is a key factor, successful algorithms that are computationally intensive such as convolutional neural networks are probably not suitable, and less computationally-intensive models such as support vector machines are more suitable.[36] This field will develop rapidly as more drone data is collected.

TRACKING ANIMALS WITH RADIO TRANSMITTERS AND DRONES

Aside from wildlife surveys, which count static averages of populations in specific areas, biologists sometimes want to track wildlife to establish patterns of behavior. An established technique has been to attach VHF radio transmitters to individual animals so scientists on foot or in airplanes can locate and track them. Researchers have recently started to investigate the use of drones to locate animals with a VHF collar. Such work is nascent, but it is a promising way to reduce the cost and effort that biologists currently incur while tracking wildlife.[37] In addition to VHF transmitters, researchers use GPS loggers that transmit their data to phone networks or satellites. In areas where phone networks are unavailable and satellite uploads are too costly, there might be opportunities to use drones as data relays or data mules. In such a setting, drones would fly over areas where animals with GPS loggers are present and such loggers would upload data to the drone once a connection has been established; the data would then be relayed or stored on the drone. Experiments with such systems are now being undertaken by several research groups.

LAND-COVER CLASSIFICATION AND CHANGE DETECTION

Monitoring changes in land cover is one of the key tasks for conservation. Such monitoring entails determining whether certain land covers such as pristine rainforest are being converted to other land covers such as oil palm plantations or are being degraded by logging. Most of this monitoring is currently conducted by analyzing satellite images. The resolution of satellite images continues to improve, as does the frequency with which satellite images are captured.

An example of animal detection with computer vision algorithms.

The cost of satellite imagery is also coming down. However, drones can still compete with satellites in certain respects, while complementing satellite imagery in others.

The use of drones for such efforts is still in its infancy, but recent studies are promising. A key aspect of any land-cover classification study is to assess the accuracy of the resulting land-cover map against control points. Traditionally, many studies have used ground control points for the validation of land-cover classification based on satellite imagery. In such studies, the assessments of the land-cover classification from satellite image analysis are compared to the land-cover type determined from the control point during the ground surveys, and accuracy scores are calculated for how well the satellite image-based analysis compares to the ground control points.

Recently researchers have started to use drones as an alternative to traditional ground-based validation of satellite-based classifications.[38] The higher resolution of drone-based imagery can be used to calibrate satellite images by figuring out what features on the ground correspond to what features in satellite images. These studies have been conducted with standard RGB cameras. However, studies that use hyperspectral or multispectral images to classify land cover are becoming more common.[39] Hyperspectral cameras are used to measure the radio frequency spectrum of natural light reflected from vegetation and ground cover in great detail (multispectral cameras do this as well; hyperspectral cameras take in more detail than multispectral cameras, though there is not a clear dividing line), which can then be used to algorithmically determine which plants, trees, or minerals are present.

Although multispectral systems have shrunk in size and weight and can be used in small drone systems, hyperspectral cameras still tend to be relatively large and heavy (about 2 kilograms), which limits their use to larger drones.[40] The development of smaller and lighter Lidar (light detection and ranging) systems also promises to open a whole suite of interesting research applications that require high-resolution point clouds to derive forest metrics.[41] But

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even given these constraints, the applications[42] that have been used at a landscape scale range widely. They include mapping of moss beds in the Antarctic,[43] mapping of canopy cover and gap sizes,[44] using aerial images of canopy gaps to assess biodiversity of the understory in a forest,[45] land-cover mapping,[46] and assessing soil erosion.[47]

Researchers are also using drone imagery to assess habitat quality for wildlife. Such studies often determine land-cover classifications based on orthomosaics from drone-based images and link these to bird breeding density[48] or bird flight pathways.[49] Although land-cover change monitoring is one of the major applications of satellite-based monitoring, drones are ideal for this purpose because of the very high-resolution images they provide and the flexibility with which they can be deployed to capture images.[50] Small-scale changes can be readily detected and flights can be programmed to specifically monitor forest boundaries or certain key areas at high risk of human encroachment. This makes drones suitable as a monitoring tool for conservation workers, but also for local communities that would like to monitor the areas they manage.[51] Local communities could use drones to detect potential illegal incursions into their area, for instance, as well as to monitor REDD+ (Reducing Emissions from Deforestation and Forest Degradation) projects. Using drones also would potentially allow the communities to regularly obtain data on the above-ground carbon stock present in the forests they manage for carbon projects. This could reduce costs compared to present practices, in which specialist teams conduct such work.

COMPUTER VISION AND LAND COVER

As with detecting and counting wildlife, researchers are using computer algorithms to automatically detect landscape features in images. Studies have examined how to automatically detect trees with various methods, such as counting oil palm trees in plantations using the point cloud generated by photogrammetry software[52] and automatic tree crown segregation for tree detection based on RGB images.[53] Models to automatically detect tree species are also being developed.[54]

POACHING

Wildlife poaching is a major threat to many species and has sharply reduced the wild numbers of iconic species such as rhinos, tigers, and elephants. In South Africa alone, the total number of rhinos killed in 2014 was 1,215.[55] A persistent difficulty in curbing these crimes is detecting poachers before they reach the target species. Drones have been deployed to achieve early detection of poachers and their potential target species.[56] Operations using drones to prevent poaching have been started in Nepal[57] and several other locations around the world.[58] Although the effectiveness of such drone deployments remains unclear, thermal cameras have been used in South Africa to detect and intercept poachers at night.[59]

The most sophisticated and potentially most successful approach uses models that combine information—such as the locations of previous rhino kills, satellite data, and knowledge about infrastructure and rhino movements—to predict where rhinos will be at times when poaching is highly probable. Rangers and drones are then deployed in such areas to intercept the poachers before they reach their target.[60] This approach has been claimed to be very successful.[61] Although such methods can work in the relatively open savannah-woodland areas, current sensors do not allow for detection of humans or animals through the thick canopy of tropical rainforests. But video from drones might still be useful in detecting smoke plumes. Video footage acquired by the group Conservation Drones in Indonesia and Congo-Brazzaville allowed for the detection of smoke plumes, which can be the sign of fresh forest clearing or of bushmeat poachers drying animals on racks in the forest. Such information could facilitate more targeted deployment of local rangers to increase their success in intercepting bushmeat poachers or people clearing forests.

CONCLUSION

The use of drones for conservation has just started and is showing promising results for the detection of wildlife, classifying and monitoring land cover, and reducing poaching. The next few years will likely see very rapid

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Deforestation in Sumatra, Indonesia, can be seen in the bald patches in the right image.

developments on several fronts that will increase the use of drones for conservation. First, drone flight durations will continue to increase due to improvements in the systems that power drones, such as batteries and solar cells. Second, the rapid development of sensors will continue with increasingly smaller sensors that can be used in drones. Specifically, the development of small Lidar, hyperspectral, and thermal sensors will benefit conservation, as will advances in smaller and higher-resolution standard RGB cameras. Third, drones will become more user-friendly, which will lower barriers to entry. Fourth, data analyses for both wildlife detection and land-cover classification will become more sophisticated, which will aid the efforts of conservation workers. Fifth, onboard processing of images and video will allow for automatic detection of wildlife and humans. In combination with better transmission systems, this information then can be relayed in near real time to rangers on the ground so they can adapt fast to changing situations in the field. Sixth, the simultaneous, coordinated use of multiple drones (swarming) will allow for more effective mapping and monitoring of large areas. Seventh, further integration of the various technologies that conservation workers are using will be necessary to face the increasing challenges.[62] §

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CHAPTER 8: DRONES AND THE PROTECTION OF HUMAN RIGHTS

KONSTANTIN KAKAES

An American ScanEagle drone flying over the Pacific Ocean. Dutch peacekeepers are flying the same type of aircraft over Mali in the hopes of helping to bring an end to a long-running civil war with Tuareg militias. U.S. Navy photo/Joseph M. Buliavac.

This chapter asks how drones are being used to protect people's "life, liberty and security"—the first rights set forth in the Universal Declaration of Human Rights.[1] The United Nations is flying unarmed drones over war zones in the Democratic Republic of Congo (DRC) and Mali, and the Organization for Security and Cooperation in Europe (OSCE) is using drones to monitor the war in eastern Ukraine. Drones are not decisive in any of these conflicts; they are, however, new. Surveillance drones cannot, of course, stop wars in and of themselves. The information they gather can perhaps help bring peace sooner and, in so doing, protect human rights.[*] As Hedley Bull wrote in his 1977 classic *The Anarchical Society*, "justice, in any of its forms, is realisable only in a context of order."[2] The OSCE, like the UN, is an intergovernmental organization, which is to say, it is comprised of national governments. As such, its strengths and limitations are distinct from those of non-governmental human rights advocacy organizations such as Amnesty International or Human Rights Watch. Such groups are interested in using drones,[3] though they have not done much yet, with the exception of disaster response (which is discussed in Chapter 6).[4]

DRONES AND A CHANGING UNITED NATIONS

The UN's use of drones is part of a larger change in the scope and size of its peacekeeping missions. There are currently about 125,000 UN peacekeeping personnel—military, police, and civilian—deployed around the world in 16 missions.[5] Peacekeepers come from over 120 countries, and the peacekeeping budget is about $8.2 billion. This is at least seven times greater, in terms of both money and personnel, than UN peacekeeping

* This chapter does not address the use of armed drones by national governments, in particular the government of the United States. These are worthy questions, addressed by UN Special Rapporteur Ben Emmerson in a number of reports: Report of the Special Rapporteur on the Promotion and Protection of Human Rights and Fundamental Freedoms While Countering Terrorism, 22d Session of the Human Rights Council, U.N. Doc. A/HRC/22/52 (Mar. 1, 2013) (by Ben Emmerson); Report of the Special Rapporteur on the Promotion and Protection of Human Rights and Fundamental Freedoms While Countering Terrorism, 25th Session of the Human Rights Council, U.N. Doc. A/HRC/25/59 (Mar. 11, 2014) (by Ben Emmerson); as well as in a number of chapters in Peter Bergen and Daniel Rothenberg, eds., Drone Wars: Transforming Conflict, Law, and Policy (New York: Cambridge University Press, 2014). This chapter also elides discussion of the use of drones by military alliances such as NATO, even when, as in anti-piracy patrols in the Indian Ocean, such drone use is also arguably aimed at protecting the life, liberty and security of, in this example, merchant sailors. See, for instance, Craig Hoyle, "Dutch fly first ScanEagle mission off Somalia," Flightglobal, August 31, 2012, http://www.flightglobal.com/news/articles/dutch-fly-first-scaneagle-mission-off-somalia-375990/.

An American soldier launches an RQ-11 'Raven" drone on a training exercise in New Mexico. Dutch peacekeepers are using the same model on their deployment in Mali.

WISCONSIN NATIONAL GUARD PHOTO/Staff Sgt.Alyn-Michael Macleod.

activities in 1999.[6] The expansion of UN police activity has been even more dramatic, increasing from about 1,500 deployed UN police officers twenty years ago to over 12,500 in 2015.[7] These larger numbers are needed because peacekeepers are no longer monitoring truces, as in the Golan Heights or Cyprus, but proactively intervening in wars. As a forthcoming report by a UN panel puts it, "In the absence of a peace to keep, peacekeepers are increasingly asked to manage conflict."[8] Herve Ladsous, the top UN peacekeeping official, has argued that unarmed drones are the "tool of choice" for tracking "the movements of armed militias to protect civilians."[9]

Unarmed drones are primarily a mechanism for gathering information. But as Sharon Wiharta and Anna Wiktorsson, researchers at a Swedish government institute, point out, "Information is useful for the decision-making of the mission leadership only if the raw data can be analysed quickly and accurately, and the intelligence is then swiftly distributed to those who need it across the different components of a peace operation."[10] This has been a problem for the UN, because, as Melanie Ramjoue (who at the time was a UN official in the DRC) has written, "States have historically been opposed to granting the UN any intelligence-collection powers, fearing that such a role could lead to violations by the UN of national sovereignties."[11]

The UN's remedy for this has been the establishment of strategic analysis units called Joint Mission Analysis Centres (JMAC) in which military, police and civilians work together in the field to analyze intelligence[12] and tactical analysis Joint Operations Centers (or JOC)[13]. In Mali, the UN has created a larger intelligence shop, the "All Sources Information Fusion Unit" (ASIFU) an, "unprecedented military intelligence and analysis capability for a UN mission."[14] The distinctions among these various units can be confusing even to those within them*; the short version is that the UN is devoting more and more resources to intelligence and surveillance.

The UN has used dedicated surveillance aircraft for many decades, first employing them in the Sinai in 1956.[15] It also has used transport aircraft as dual-purpose reconnaissance platforms, in Lebanon, Yemen, and Central America.[16] But as Kevin Shelton-Smith, a UN aviation officer, has written, the "greatest change to UN aviation is likely to come in the form of unmanned aircraft."[17]

The first UN force to operate a drone was MINUSTAH, the peacekeeping force in Haiti, in 2007:

> The small prototype was only in the mission for a short time, however. When the Brazilian battalion that brought it was rotated out, it was also withdrawn. Still, it proved useful for distributing leaflets. It did not have a significant observation capacity. Some soldiers suggested that a UAV could be used to draw fire from the bandits, thus exposing their positions. The UAV was not equipped for night observation.[18]

The significance of the UN's experience in Haiti, though, lies not in its use of UAVs but in its successful use of information to make civilians safer.† Helicopter-based aerial observation, both during the day and at night was helpful to the UN in its effort to defeat armed gangs. Ultimately, "intelligence-led operations constituted a pioneering approach that succeeded in Haiti."[19]

The only drones operated not by individual troop-contributing countries but by the UN mission itself are in the Eastern Democratic of the Congo, as part of MONUSCO, the UN peacekeeping mission in the Congo. MONUSCO is commanded by Lieutenant-General Carlos dos Santos Cruz, a Brazilian who previously had lead the UN mission in Haiti in 2007 during the successful anti-gang operations there. The UN's use of drones in the Congo is discussed at length in Chapter 10.

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* To wit: "The distinction between JMAC and JOC roles was often blurred. To start, the JOC was inappropriately named, since it acted primarily as a conduit for information not operational orders ('Joint Information Centre' or JIC would be a better name than JOC)" A. Walter Dorn, "Intelligence-Led Peacekeeping: The United Nations Stabilization Mission in Haiti (MINUSTAH), 2006–07," Intelligence and National Security 24, no. 6 (2009). According to Dorn, as of 2015, the UN has made little or no progress at UN headquarters on such joint intelligence efforts.

† In more recent years, the UN has worked with the International Organization of Migration, an independent intergovernmental agency, to use small drones to make maps of Port-Au-Prince, as part of ongoing efforts to rebuild after the 2010 earthquake. See "UNOSAT carries out first UAV mission for IOM in Haiti," UNITAR, February 17, 2012: http://www.unitar.org/unosat-carries-out-first-uav-mission-iom-haiti.

The UN used unmanned surveillance intermittently in Chad from 2006 to 2009. According to John Karlsrud, a former UN official, during a 2009 cross-border invasion from Darfur (of Chadian opposition forces), "the drone capability proved very useful to the mission, as UN forces could closely monitor the movement of the opposition forces and enhance the protection of refugees, IDPs, and humanitarian aid workers."[20]

Dutch peacekeepers in Mali are operating both ScanEagle and Raven UAVs.[21] The ScanEagle, made by a unit of Boeing, is a mid-size drone that can stay in the air for as long as 20 hours, while the Raven is a smaller, hand-launched drone. The Dutch ScanEagles are based in Gao, while the Ravens are deployed with Dutch special forces soldiers. In May, 2015 Swedish peacekeepers in Timbuktu deployed Ornen*, Svalan, and Korpen drones.[22]

It is difficult to say exactly what effect the Dutch and Swedish UAVs are having on the life, liberty and security of Malian citizens. Although a peace accord was signed in June, 2015, six UN peacekeepers (from Burkina Faso) were killed in an ambush in early July.[23]

A December 2014 UN report explains the technological shortfalls that UN peacekeepers now face:

> especially in the areas of command and control, monitoring, reconnaissance and reporting, and information and communications technologies, peacekeeping operations simply do not currently possess anything approaching adequate numbers or types of technologies that militaries and police forces around the world accept not only as commonplace, but also as foundational to successful operations. This must change.[24]

The December report goes on to call for more "systematic use of commercial satellite imagery" and of drones: "unmanned aerial systems constitute an indispensable source of information and should not only remain part of the peacekeeper's toolkit, but their use should also be immediately expanded." The report points out that small, hand-launched drones would be particularly useful to UN forces in the field.

There is conflict within the UN between troop-contributing countries like Bangladesh and India, who are reluctant to put their soldiers in danger, and both member states and UN officials who are arguing for more interventionist policies.[25] As a forthcoming report of the High-Level Panel led by José Ramos Horta, a former President of Timor-Leste and a Nobel peace price laureate, put it, "Every peacekeeper—civilian, military, police—must do all they can when civilians are under imminent threat ... Command and control is too often undermined by national restrictions revealed in the field. This must not be tolerated."[26]

Horta's report was referring to restrictions placed by troop-contributing countries on their soldiers. However, restrictions by host governments who claim the privileges of sovereignty without being able to deliver on the responsibilities of sovereignty also affect the UN.

The UN has tried to deploy drones to monitor the ongoing conflict in South Sudan, but has been blocked by the South Sudanese government.[27] Ladsous has said, "The use of such drones during the recent crisis in Jonglei [South Sudan] in order to map the movements of armed militias would have enhanced the capability of the Government of South Sudan and of UNMISS [UN Mission in South Sudan] to protect civilians by preventing violence and displacements."[28] Ladsous has also advocated for the UN to use drones in the Central African Republic.[29]

However, as Anthony Blinken, the U.S. Deputy Secretary of State, recently said, "At the end of the day, however, the kinds of conflicts we are talking about—the kinds of challenges we are asking our peacekeepers to confront—will not be resolved simply with more helicopters or more troops. They have political causes. They require political solutions."[30]

THE OSCE IN THE UKRAINE

Political solutions can be difficult to reach. In eastern Ukraine, Russian-backed separatists have been fighting with the Ukrainian government since the spring of 2014, despite a September, 2014 ceasefire signed in Minsk. The Organization for Security and Cooperation in Europe (OSCE), an intergovernmental organization with 57 participating states has been charged with monitoring the ceasefire.[31] The OSCE Special Monitoring Mission to Ukraine (SMM) was first deployed before the ceasefire, in March 2014, shortly after the beginning of the conflict in Eastern Ukraine.[32] According to the OSCE, "its main tasks are to observe and report in an impartial and objective way on the situation in Ukraine; and to facilitate dialogue among all parties to the crisis."[33] The OSCE has 756 international staff in the Ukraine charged with monitoring both the ceasefire and the humanitarian situation more broadly. It also has a fleet of four UAVs under its authority. (One crashed in February 2015.)[34]

The Schiebel S-100, a medium-sized unmanned helicopter, costs about $400,000 per unit.[35] The OSCE hasn't bought them outright, and is instead relying on a contract with Schiebel, an Austrian company, who also operate the drones. The S-100 can fly 50-80km from its base station and can carry about a 110 pound payload for as long as 6 hours, flying at a cruise speed of 60 miles per hour. [36] The S-100s first flew in the Ukraine on October 23, 2014.[37] Unlike the UN, who, since they use their drones to support troops on the ground, guard the information the UAVs gather quite closely, the OSCE observers issue near-daily reports of what the drones have seen, along with reports from observers on the ground. They even sometimes release imagery.[38]

The OSCE's drones are frequently jammed and shot at by combatant parties.[39] Weather, however, is a bigger problem

* These are Swedish versions of the American Shadow, Wasp and Puma, respectively. The Shadow is similar to a ScanEagle. The Puma and Wasp are made by AeroVironment, the same firm that makes the Raven. The Puma is slightly bigger and the Wasp slightly smaller.

Pro-Russian separatists patrol in the eastern Ukrainian city of Makeyevka in February, 2015. The OSCE monitoring mission can see such tanks with its drone.

VASILY MAXIMOV/AFP/Getty Images

than jamming.[40] Perusing the OSCE's reports, one can see the virtue of publicly accessible, verifiable information.

On June 3, 2015, after fighting started early in the morning around the town of Marinka (23km south-west of Donetsk's center), the OSCE drone, "observed intense shelling targeting an intersection of the H15 highway 3.5km south-west of Marinka. The UAV spotted four 2S3 Akatsiya 152mm self-propelled howitzers 9km south-west of the town at 15:30hrs."[41] A few days later, on June 6th, monitors couldn't go to the village of Shyrokyne, because it was unsafe. "However, an SMM UAV on 6 June spotted two mortar positions in immediate proximity to civilian houses in 'DPR' [Donestsk People's Republic]-controlled areas of the village and the following day a burning building, also in the village itself."[42] The next day, "the UAV spotted 35 military trucks and 25 armoured personnel carriers. Also, of note was a concentration around "DPR"-controlled Oktyabr (85km south of Donetsk), namely, three artillery pieces and two MBTs."[43]

A week later, the observers note that "despite claims that the withdrawal of heavy weapons was complete", ground observers saw thirteen tanks and four armored vehicles, while an OSCE drone saw "ten MBTs [Main Battle Tanks] (unknown type) and 27 armoured vehicles in Komsomolske ('DPR'-controlled, 43km south of Donetsk), as well as four self-propelled artillery pieces (likely 122mm 2S1 Gvozdika) approximately 1km west-south-west of Vasylivka ('DPR'-controlled, 50km south-south-east of Donetsk)."[44]

Another report reads, "In the early evening hours of 21 June [2015], the SMM unmanned aerial vehicle (UAV) spotted burning houses in Shyrokyne."[45] These reports continue along similar lines. Reading them gives some texture to the question of how observation drones can protect civilians. The drones do not stop the houses in Shyrokyne from burning. But surely it does some good to have independent, verifiable, and publicly accessible information from the midst of a war zone? As Paul Fritch, an American diplomat who was previously the OSCE's chief of staff, puts it, "[The OSCE observer mission] has done difficult, dangerous work, often in harsh conditions, and has gradually established itself as a credible stabilizing force. In a conflict where propaganda and disinformation have flown more freely than artillery shells, the SMM's sober, factual reporting has been an invaluable asset to would-be peacemakers."[46] The UAVs have contributed to this effort. As Fritch notes, "skeptics will point to the fact that for all of this activity, the OSCE has not ended the violence, prevented Russia's annexation of Crimea, or slowed the advance of Russian-backed separatists in Donbas."

NGOS AND UAVS

The OSCE's failure to end the violence in Ukraine raises the question of what the virtue of information without political will is. As Fritch writes, there *is* virtue, but that virtue is limited.

David Whetham of King's College London posits that the information drones gather can have value as a deterrent:

> Unarmed, unmanned aerial vehicles (UAVs) with surveillance capabilities – 'flying cameras' – could be deployed under a relatively uncontroversial United Nations Security Council Resolution (UNSCR) in a matter of days or even hours to nearly anywhere on the planet to stand witness and record events on the ground as they happen. If this could be done in a suitably public way, thus deploying them with as much fanfare as possible to ensure that belligerents are aware of what is going to happen, the fear of being observed may be enough to modify behaviour.[47]

Perhaps. However, such hopes for deterrence seem more aspirational than actual. As Daniel Gilman of the UN's Office for the Coordination of Humanitarian Affairs says, "I'm not convinced so much about the deterrent effect of drones. Just because I think people are assholes."[48] A project called the "Satellite Sentinel Project," which was funded by actor George Clooney, attracted a lot of attention in 2010 and 2011 for using high-resolution commercial satellite imagery to search for evidence of war crimes.[49] However, as some of the participants in the effort later wrote in the *Georgetown Journal of International Affairs*, in a remarkably self-critical post-mortem, "The experience of the Satellite Sentinel Project (SSP) suggests that attempting to enhance the situational awareness of policymakers and the public does not appear by itself, at least in the case of Sudan, to directly affect whether, and to what degree, governments respond to mass atrocities as they occur."[50]

Because of the United States' use of armed drones, many human-rights advocates are wary of drones entirely. As Gilman says, "Right now there is a civil war [in the human rights and humanitarian communities] because you have activists who see them as a tool of surveillance, and another group who just see them as a tool."[51] Gilman points out that at political protests the number of protesters is often a matter of controversy. If multiple independent teams can use UAVs to come up with verifiable population counts, he says, it might be useful.

But, Gilman says, the most contested space is "the real human rights stuff ... How do you give people the freedom to document abuses without creating broader risks?" he asks. Christoph Koettl of Amnesty International says that he sees two major goals for the human rights community in using UAVs. The first is indeed documentation of abuses—evidence gathering. The second is advocacy and public campaigning, which he says is further along.

The OSCE flies Schiebel S-100 drones in its monitoring mission in the Ukraine. A group called MOAS is using the same drone to search for boats carrying refugees in the Mediterranean.

With regard to documentation of abuses, he says the "feeling at Amnesty is that we wouldn't break the law," which could make drone use to document abuses a non-starter if governments seeking to hide human rights violations simply decree that drones are prohibited. In many areas around the world, from Syria to the Russian/ Ukrainian border, human rights workers are already using satellite imagery, which can be useful. But the greater detail of drone imagery would be useful, Koettl says, in order to be able to see insignia of specific military units and establish command responsibility.

"Are we spying?" he asks, rhetorically. "Not really," he answers his own question: "we just want to document human rights violations from both sides," in any given conflict. He speculates that in the short run, the most common type of drone imagery used by human-rights advocates might be that provided by third parties, as sometimes happens with, say, mobile phone video. It "could just fall into our hands," he says. Even in this case, however, Koettl is reticent about publishing personally-identifiable information. "We might blur out the faces even of perpetrators," he says, while holding on to the unblurred images for possible trial at the International Criminal Court or some other venue.

But even if Koettl doesn't think of drone imagery as spying, others might. Part of the task of human rights activists who want to put drones to use is a shaking off of the stigma that unmanned aircraft acquired following American drone strikes in Pakistan, Yemen, and elsewhere. With the proliferation of small consumer drones, that process is well underway. But even as the process of assimilation continues, the fact remains that drones are capable of gathering information unilaterally. Norms are presently forming about their use.

Wikimedia Commons

A 2013 paper by Rahul Chandran and Andrew Thow argues that, "humanitarians must adapt to the idea of information as a basic need in humanitarian response."[53] Taking this claim seriously requires, they say, a re-ordering of priorities. The paradox in their argument is the claim that "information creates most value when it can be shared widely and freely."[54] There is much truth in this statement.

However, their call for "standards for the ethical use of new forms of data, including protocols for protecting privacy and guaranteeing informants' safety," has not, and probably cannot, be entirely satisfactorily addressed.[55] It isn't possible to come up with standards in a way that square the circle. As Gilman says, figuring out how to construe privacy in a humanitarian crisis—whether violent conflict or natural disaster—is not straightforward. "Consent isn't a very useful thing in humanitarian crisis because the power dynamics are too skewed....the responsibility is much more on people collecting the information to make sure it is done responsibly. There needs to be an assessment of what the actual risks are to people."

These considerations hold equally, in principle, for satellite imagery and drone imagery. Josh Lyons works as a satellite and drone imagery analyst for Human Rights Watch. "My primary focus within satellite work is as an extreme guardian of quality control, anticipating every single conceivable mistake that we might make in order to avoid catastrophic failure," he says. And such mistakes of interpretation are easy to make. The higher resolution of drone imagery in principle might help, he says, as might the fact that drones are relatively cheap and can fly at specific times, instead of satellites that orbit in relatively difficult-to-change trajectories.

"From a human-rights perspective, a large number of [locations in conflict zones] change hands frequently. In order to ascribe any legal responsibility, or attribution for one of these different armed factions for particular potential violations, indiscriminate shelling, destruction of civilian property, you have to have a much finer time series in order to break down what happened on what date and what week," he says. But even such more detailed aerial imagery is limited. "Photo-interpretation-based analysis of imagery for human-rights applications is fundamentally hamstrung... without having ground information to cross-validate, without access to people on the ground to overcome the fundamental limits of visual interpretation of imagery alone," Lyons says. The potential of aerial imagery to corroborate eyewitness evidence—whether from a satellite, manned aircraft, or drone—is profound, he adds.

Lyons remembers a story from 2013 in Baga, a town in Nigeria. "The testimony we had was the Nigerian army had come in a light engagement with Boko Haram. Boko Haram left and Nigerian forces there decided to take it out on the local population. They burned down 2,500 homes. The testimony we had was that they [the Nigerian military] started the fires." Lyons had high-resolution satellite imagery, from about 3 weeks before the fires in question, and also from a week after. But "attribution for that damage is still slippery," he says. Using another satellite called MODIS, which takes thermal images at low resolution but more frequently, he found "a time stamp for the fires starting in the evening, lasting through the night, continuing through sometime around noon the next day. For these fires to be detected by this very low resolution satellite these fires have to be really big. It was absolutely conclusive and compelling—it matched the testimony flawlessly."

The problems encountered by the Satellite Sentinel Project in Sudan reiterate Lyons' point: "The most important issue was the inherent limitations on analyzing remote sensing data without reliable ground confirmation. Satellites could offer a rare glimpse into the highly non-permissive Sudan-South Sudan border areas. However, imagery still represents only a single source of data about alleged events within a dynamic conflict zone. Though the [Sentinel] team strove to draw definitive conclusions about the conflict, remote sensing analysis alone could not result in conclusive knowledge of a situation, only interpretations," they wrote in their self-criticism.[56] As in examples from wildlife conservation, the higher resolution of drone imagery can be used to aid in the interpretation of satellite images that cover a broader area—the two can complement one another.

Because of the coverage of satellite imagery, it will continue to be a valuable tool. However, there is one major problem with satellite imagery: clouds. "There are still parts of the world, parts of Congo and Indonesia, where there are some satellites that have never detected a cloud-free pixel in certain areas," says Lyons. He thinks drones could be useful in such cases. He remembers attacks in Burma a few years ago: "[The] first round of arson attacks had occurred in June, and it was probably October before there was an image acquired... it was a major, major anti-Rohinga attack, had destroyed thousands of buildings. That place was under cloud for 4 months. It had days when it was sunny but satellites are not acquiring every day." Bangui, the capital of the Central African Republic, went into cloud for 2.5 months—"Not a single cloud-free acquisition," he says, except for radar. Radar imagery, however, he says, is very difficult to analyze. So despite the collapsing price of satellite imagery—a non-emergency tasking, which usually gets an image within a week, costs him €350 for a 25 square km image—drones can complement satellite imagery because of their higher resolution, ability to fly below clouds, and greater flexibility in timing.

Human-rights organizations like Amnesty International or Human Rights Watch have a fraction of the resources of the United Nations; their power consists almost entirely of moral suasion. If one believes that such work is, in general, worthwhile, then it seems there is a niche in which drones can help document human rights violations, and so help curb them. But, as in documentation of human rights violations by other means, including eyewitness testimony, knowing about something is but the first step in doing something about it. §

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

FAINE GREENWOOD

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.

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CHAPTER 10: THE UN'S DRONES AND CONGO'S WAR

KONSTANTIN KAKAES

The eastern provinces of the Democratic Republic of the Congo have been at war, of varying but incessant intensity, for nearly 20 years. The outbreak of war was catalyzed by a Rwandan invasion in 1996, in the aftermath of the 1994 Rwandan genocide. The invasion provoked a war that spanned the Congo* and ended when Mobutu Sese Seko was overthrown in May 1997. Laurent Kabila, who replaced Mobutu, and his son Joseph, who took power after Laurent's assassination in 2001, fought with their former Rwandan patrons and a slew of other combatants in a second round of fighting from August 1998 to June 2003. After the 2003 cease-fire, fighting has continued in the east until the present.†

United Nations peacekeeping forces arrived in the DRC in 1999 and have remained there ever since.[1] The UN contingent is called MONUSCO, the French acronym for "United Nations Organization Stabilization Mission in the Democratic Republic of the Congo." Its present mandate, most recently renewed in March 2015, says that MONUSCO's top priority is the protection of civilians.[2] It is authorized, on paper, to take "all necessary measures" to protect "civilians under threat of physical violence, including by deterring, preventing and stopping armed groups from inflicting violence." Lieutenant-General Carlos Alberto dos Santos Cruz, from Brazil, is MONUSCO's military commander and is in charge of nearly 20,000 UN soldiers and five drones. The drones were first deployed in December 2013, in Goma, a city in eastern Congo where MONUSCO has its headquarters. What role have the drones played in protecting civilians over the last year and a half, and what can they accomplish in the future?

The first problem with drones, Santos Cruz says, is lowering expectations. One goal of drones was to help contain cross-border arms smuggling, he notes. But, he asks, "if there are three or four rifles in a boat hidden in the middle of fish, how can you see them?"[3] Drones, he says, need human sources to give context. This is not something the UN has historically been good at. "Intelligence used to be kind of a dirty word in the UN," says Chris Johnson, a U.S. Army officer who is Santos Cruz's deputy head of intelligence.

* We will use Congo and DRC interchangeably in this essay, which does not discuss the neighboring Republic of Congo.

† This chapter does not treat the history of these wars in any detail. As Jason Stearns writes, "The conflict is complex and knotted, with dozens of different protagonists. The long history of state decay in the Congo—or, more accurately, the failure ever to build strong institutions—has meant that actors have proliferated, competing for power and resources in the absence of a strong government. At the height of the war, there were upwards of forty Congolese armed groups in the eastern Congo alone, while nine different African states deployed troops." Stearns's book, Dancing in the Glory of Monsters (New York: PublicAffairs, 2012), along with Gérard Prunier's Africa's World War: Congo, the Rwandan Genocide, and the Making of a Continental Catastrophe (New York: Oxford University Press, 2008), are the best overviews of these complex, sad stories. Howard French, "Kagame's Hidden War in the Congo," New York Review of Books, September 24, 2009, is a good, shorter summary.

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A Selex Falco drone flown by American contractors in support of UN peacekeeping troops in the Congo lands at the Bunia airport.

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"I think that's slowly changing." Nevertheless, at present, Johnson acknowledges, "There's no human intelligence network like you'd find in other places."[4]

The UN's involvement in the Congo goes back to when the country achieved independence from Belgium. As Walter Dorn has written, "the peacekeeping operation in the Congo, from 1960 to 1964, was the UN's baptism by fire in nasty internal (intrastate) conflicts."[5] In 1961, the UN's second secretary-general, Dag Hammarskjold, died when his airplane crashed (over the border in what is now Zambia) en route to cease-fire negotiations for a ceasefire between the secessionist province of Katanga and the central government of the Congo.* "Aerial reconnaissance, provided by Swedish jets, was essential to predict and pre-empt Katangan attacks on UN forces," Dorn writes of the 1960–64 conflict. The Congo has been bound up for half a century not only with questions of how the UN pursues peacekeeping, but also of how it uses aerial reconnaissance.

Unmanned aircraft operated by foreign peacekeepers have flown on and off in the Congo since at least 2006, when Belgian armed forces brought drones to the capital, Kinshasa.[6] However, their systematic use by the United Nations dates to December 2013.[7] This has been the first time that the UN has used drones as a "mission asset" (i.e. integrated them into overall operations).† The UN's drones, called Falcos, were built by, and are operated by, Selex, an Italian aerospace company that is a subsidiary of Finmeccanica, a conglomerate.[8] The Falco is a twin-boomed fixed-wing drone, the size of a compact car, which is pushed through the air by a rear-facing propeller.[9] The Falco is roughly half the size of a Predator. This makes it much bigger, and thus more expensive to build and operate, than the new generation of drones built by consumer

* That crash remains a source of controversy, with Ban Ki-moon, the current secretary-general, calling for a new investigation in July 2015 as discussed in: Somini Sengupta, "U.N. Chief Calls for New Inquiry Into 1961 Plane Crash That Killed Dag Hammarskjold," New York Times, July 6, 2015, http://www.nytimes.com/2015/07/07/world/americas/un-chief-calls-for-new-inquiry-into-1961-plane-crash-that-killed-dag-hammarskjold.html?_r=0.

† Though this is often presented as a crucial step forward for the UN, as opposed to in the past when troop-contributing countries brought drones with them, the development is, to an extent, accidental. The UN asked troop-contributing countries to bring UAVs to the Congo, but no member nation was willing to contribute drones. The UN thus put the process out to commercial vendors and received eight bids. The UN sought a UAV that could identify a two-meter target from a distance of five kilometers and that would be able to relocate via C-130 aircraft within 48 hours. It considered a number of options, including the Elbit Skylark, Elbit Hermes 450, MMist SnowGoose, Aeronautics Aerostar, and IAI Searcher. For more, see A. Walter Dorn, Air Power in UN Operations: Wings for Peace (Farnham, UK: Ashgate Publishing Company, 2014), 292.

companies. Its cost and size are necessary if it is to have the range, endurance and capability that the UN requires. In many ways, this sets it off in character from something like a DJI Phantom. However, both small and large drones gather visual information from above. The questions raised about how they do so, and how that information is used, are similar regardless of the size of the drone.

The UN pays Selex $13 million annually to run the UAVs (which was the cheapest of the bids it received).[10] The Falco, says Lieutenant Colonel Matt White, a British artillery officer who is currently the head of UAS operations for MONUSCO, is "absolutely outstanding value for money. It brings situational awareness to the mission that you previously didn't have. I wouldn't like to guess at the magnitude improvement, but I would suggest it's large."[11] The Falcos typically fly two missions a day, White explains, from Monday to Thursday. They fly once a day on Fridays and Saturdays, and on Sundays they rest. Each mission is about five hours—the Falco's endurance is longer, but the missions are planned to allow for contingencies. "Sometimes you have to spend a long time circling an area to get the pattern of life established. Other times it's dynamic—'I need to have a look at that now'—and we find stuff that could be actionable straight away," he says. Selex maintains ten staff members in the DRC to operate the UAVs—pilots, sensor operators, engineers, and mechanics, most of them Americans with experience operating drones in Iraq, Afghanistan, and elsewhere.

For the first 11 months of their operation, the Falcos were based at the airport in Goma, a few miles from White's office at MONUSCO's headquarters on the shore of Lake Kivu. In November 2014, Steven France, White's predecessor, moved them to Bunia, the principal city of Ituri, a region about 200 miles north.[12] "The reason we did that was not because they weren't needed in Goma, but because there was some pretty atrocious activity going on outside Beni in November," France says. Beni is a smaller city about halfway between Goma and Bunia, but its airport's runway had too much gravel for the Falco to take off from and land on without being damaged.

"In October and November 2014, a series of attacks took pace in the Beni area that killed more than 200 people and displaced several thousand people," a January 2015 UN report recounts.[13] Those attacks are thought to have been made by an armed group called the ADF (Allied Democratic Forces). The report discusses the leaders of the ADF, who "oversee a system that imposes punishment such as crucifixion; death by stoning; severe beatings even just for speech considered subversive; imprisonment in pits, underground cells and an 'iron maiden' ... starvation during imprisonment; and summary execution." It also explains that between January and September 2014, one center alone dedicated to helping "children associated with armed groups" received 1,125 children between eleven and seventeen years old in the first nine months of 2014.[*] The ADF is an Islamic group. However, the UN report says that there is no "credible evidence suggesting that ADF has, or recently has had, links to foreign terrorist groups."[14] Outside experts dispute the role that ideology plays in motivating the ADF; some argue that it ought to be thought of as a criminal gang, while others see it as an ideologically-driven insurgency.

Though the redeployment of the drones took place quickly, they were unable to be of much use against the ADF, says a UN official.[15] The ADF is operating in the foothills of the Rwenzori Mountains, in triple-canopy jungle. The Falco uses a Wescam MX-10 sensor to see.[†] The MX-10 carries both visual and infrared cameras, which can see heat, whether from human bodies or cooking fires.[16] However, the sensors cannot effectively penetrate the canopy. The Falcos were better at aerial reconnaissance than helicopters, which were already being used; they found a whole village that couldn't be seen from helicopters. However, this UN official notes, you have to give the drones "something to look for.

* These children were recruited by the ADF as well as other armed groups.

† One of the drones also carries a synthetic-aperture radar, but this has seen only limited use, according to White, who says, "It's quite limited in terms of what it can provide you here. It's useful in big, open spaces looking for vehicles. We don't do a great deal of that here in the Congo."

AFP Photo/Alain Wandimoyi/Getty Images

People demonstrate against MONUSCO in Mavivi, north of Beni, on October 22, 2014 after a series of massacres attributed to the ADF in which 80 civilians were killed.

One of two Falco drones that Selex is operating for the UN out of Bunia, the principal city of Ituri, near the border with Uganda.

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The ADF don't walk around with weapons. They cache them." This makes it difficult to tell whether a group of people the infrared sensors glimpse walking around the forest is composed of villagers or rebels.

On January 15, 2015, MONUSCO and the FARDC (the Congolese army) launched an operation against another group* called the FRPI (Forces de résistance patriotique d'Ituri) that had attacked a Congolese army position in Aveba, a town about thirty miles southwest of Bunia.[17] Since that attack, France says, the focus of the drone surveillance has been "almost completely FRPI." In Kagaba, a village about ten miles from Aveba, Aidivodu Gerard, the headmaster at the primary school, recounted an attack that had taken place in April. Apolina Malikizungu, a fifty-two-year-old woman, was killed. The FARDC came late, he says. It took the army half an hour. But MONUSCO came not at all. "During the daytime," he says, "things seem OK, but during the nighttime bandits come."[18] Paka Fabien Alezo, a traditional chief in Nombe, just to the north, says two young men were killed around 9 p.m. on April 14, 2015, when a militia broke down the door to the small house they were sleeping in.[19] At the hospital in Geti, a town about five miles from Aveba, Dr. Joseph Djoki Bahati says, "We have no contact with MONUSCO. We are not safe with MONUSCO. They patrol for their own security."[20] Bahati's hospital is about half a mile from a MONUSCO base, where a garrison of seventy-two Bangladeshi soldiers was commanded, in May 2015, by Major Tahsin Salehin. "We try to dominate the place by showing our presence so the FRPI cannot freely move," Salehin explains. "We send two to three patrols every day, and at night, also, with staggered timing."[21]

"There's a lot happening in every area around here because of the proliferation of the armed groups. … It's fascinating but it's also frustrating. You know you could do more," says White. "After every mission we provide a post-mission report [that] says what they found, what location, what they analyze it to be. … That's the point where someone is supposed to say dynamically, if it's an emergency, give it to the operations branch so they can do something about it. But then that demands someone to do something out on the ground. At the moment, from my limited exposure out here, people are, from the framework brigade perspective, quite fixed with all of their framework patrolling." White explains that he gives the post-mission reports that the Selex contractors create to G2, or intelligence personnel, with whom he shares an office.

"Intelligence has been underfunded for decades in the UN," says Johnson, MONUSCO's deputy intelligence officer. "Fifteen people in a division-size G2 shop is just insane." By contrast, he says, in a U.S. military deployment of comparable size, the headquarters intelligence contingent would number about 500 people. He needs many more people, he says, to analyze open-source intelligence like Twitter and Facebook, as well as to "go through with a fine-tooth comb all the post-mission reports that the UAV does." There is a strange irony at work here. The UN does not have enough personnel to effectively analyze the images it gathers with the current system; it also does not have enough UAVs to cover the enormous expanse of eastern Congo.

For instance, when three UN contractors were kidnapped in late April 2015, thirty miles north of Goma,[22] White was frustrated that the Falcos could not help in the search. "We couldn't actually find them because we didn't have an unmanned air system down here. I sat on my hands, thinking if only we had two operation sites, the one down here could be concentrating on that whilst we continue with the armed-group search in the north," he says.† It is an unenviable challenge. Although there are five Falcos in the

* Christoph Vogel, an analyst, maintains the best openly available maps of armed groups in the eastern Congo, at: http://christophvogel.net/congo/mapping/

† The three contractors were later released unharmed; it is unclear whether a ransom was paid for their release.

Congo, the Selex team can only fly one at a time. Two of the five are deployed in Bunia, where the team of contractors is, along with one ground control station (GCS). The other GCS and three drones lie fallow in Goma, where they cannot be operated for lack of funds. Only one drone can fly at a time in Bunia because the GCS can only control one drone at a time. It takes three people to operate the drone—a pilot, a sensor operator, and an engineer—who sit in the GCS, a small shipping container by the side of the runway at the Bunia airport. The DRC is the size of Western Europe; even just the eastern provinces where the war is active are large. There are always more places where the drone is not than where it is. This is, of course, true of MONUSCO's 20,000 soldiers as well.

This is a paradox that M'Hand Ladjouzi, MONUSCO's head of office in Bunia, captures well: "The main challenge of peacekeepers in DRC is that the population sees well-trained armies, well-equipped armies with all the resources they can imagine, and they can't see why the problem is still there. Then you go to side of the peacekeepers and see that the zone to be covered by one Bangladeshi battalion is larger than the whole of Bangladesh.* So you can imagine the number of miracles you have to perform in order to be present everywhere."[23]

In the case of the UAVs, this difficulty is compounded by another one: the weather. In any number of instances where the Falco's were potentially close enough to be useful, they could not fly because of the weather. "We are affected quite badly because of weather down here. Great Lakes† and non-weatherproofed aircraft don't mix very well," says White. The Falco's weather capability, says Gianfranco Fragasso, a Selex engineer who helped design the drone, is comparable to a small Cessna or other general aviation aircraft.[24]

In May 2015, as Santos Cruz traveled from Goma to Bunia, his helicopter was shot three times, puncturing the gas tank. Though fuel was leaking quickly, the helicopter landed safely. MONUSCO and Congolese army troops were sent to search for whoever fired on the helicopter, but could not find the perpetrators.[25]

It is difficult to call MONUSCO a success. The ongoing violence—and severe poverty—in the DRC are heartbreaking. The Congolese government wants the UN to leave, seeing its presence as an infringement of sovereignty.[26] The UN's failure stems in part from a lack of resources and a lack of political will from the UN as a whole to take more assertive action, but also in part from a disconnect between peacekeepers and the Congolese population. "Even when they escort humanitarian convoys, Pakistani, Indian battalions, they don't want to roll up their sleeves. They just watch. They say, 'We are not here to fight,'" says one aid worker with years of experience in the Congo.[27] "An abundance of examples illustrate how the interveners' inability to understand their local counterparts fuels miscommunication and misunderstanding and, at times, leads to disastrous consequences," writes Séverine Autesserre in *Peaceland: Conflict Resolution and the Everyday Politics of International Intervention*.[28] She goes on to describe a 2010 incident in which militiamen raped 387 civilians over the course of three days in Luvungi: "a patrol of Indian peacekeepers actually passed through the village while the atrocity was ongoing ."

It is also impossible to call MONUSCO a failure. "MONUSCO is not the police force of the DRC and is far too small, ill-equipped and ill-suited to stop gang, group or individual crimes," says Dorn.[29] But, he says, it has a positive effect on the strategic level. Things would inarguably be worse in eastern Congo if not for the UN's presence. Many members of the UN's staff—military, police, and civilian—work long hours at difficult jobs and navigate difficult interactions with the Congolese government. "It's not exactly a collapsed state," the aid worker says. There is, for instance, a parliament. However, "the government is no longer in control."[30] The Congo's road network is a shambles; many roads are impassable for much of the year. To drive fifty kilometers (thirty-one miles) from Goma may take four hours, if it hasn't rained for several days, allowing the mud to dry. Santos Cruz suggests that 20 percent of international actors' budgets should go to infrastructure. "The most important thing I've seen is roads and water," he says. "If you can open roads, farmers can export; the army, police, and UN can move." Even if what MONUSCO does is far short of what's necessary to accomplish its goal of "effective

KUDRA MALIRO/AFP/Getty Images

A burial ceremony for victims of an attack by suspected ADF rebels near Beni on April 16, 2015. At least 5 civilians were killed and decapitated in a machete attack.

* This is an exaggeration, but is true in spirit.

† Africa's Great Lakes are a series of large lakes in the Great Rift Valley. Goma is at the northern edge of Lake Kivu, a long skinny lake that constitutes the border with Rwanda. Bunia is near Lake Albert, which Uganda and the DRC share.

protection of civilians under threat of physical violence," it is a far sight better than nothing. The same can be said for the drones.

If you're outside in the city of Bunia when the Falco comes and goes from the airport a few miles away, you hear it clearly. This leads many locals to the mistaken conclusion that "when it is flying everyone can notice there is a drone, because of the loud noise. It's different from what we heard about American drones. … Here it is very disappointing."[31] However, as Brendan Clugston, one of the Falco's pilots, explains: "We try to stay above the ground as high as possible. We have two aircraft—one without a muffler, one with a muffler—so we have to adjust those altitudes. [We] then also adjust our position because of the reflection of sound off mountains. You try to get in a spot—I was trained on that—where you have less of that reflection."[32] Clugston has flown for SkyWest Airlines out of Houston, has taught at Embry-Riddle Aeronautical University, and has flown Predators in Afghanistan. Unless you happen to be near the airport, if Clugston is flying the Falco above you and you hear it, it is likely because he wanted you to. Many of the armed groups he sees from the air are in fact FARDC soldiers—the Congolese army, MONUSCO's complicated allies—so he sometimes gets orders to descend and deliberately make the drone heard in order to "see how they react. And we did, about 1,000 feet above the ground. They knew we were there, were running for red flags* and everything because they were FARDC."

Clugston explains that he'll use the Falco at times to check road conditions—both the physical condition of the road and the state of impromptu checkpoints that may be present. He has flown over riots and has worked with local police (via UN liaisons). Much of his time is spent, as White notes, looking at "patterns of life." Clugston explains, "If we are over a jungle area and we start to see a camp within that jungle off the main road, we are really going to pay attention to that and keep going back to that site and see how they are moving." But if any UN troops engage such groups, Clugston hasn't seen it. Any interdiction that might take place "happens after we've been pulled off station," he says. Ladjouzi, MONUSCO's top official in Ituri, where the drones are deployed, when asked what tangible effect the drones have on the situation on the ground, says, "For me, being nonmilitary, it's not that visible."

In November 2012, Goma fell to M23, a rebel group supported by Rwanda, despite the presence of UN peacekeepers in Goma.[33] M23's takeover was the most traumatic event in the recent history of the eastern Congo, setting off an epidemic of rape and summary executions.[34] In response to M23's brutality,† the UN created a new unit, called the "Force Intervention Brigade" (FIB). The FIB is comprised of about 3,000 soldiers from South Africa, Tanzania, and Malawi. The UN announced the creation of the FIB in March 2013, but the brigade did not become operational until that summer.[35] When the FIB eventually arrived in Goma, it routed M23 in a joint offensive with the Congolese Army. As James Verini writes in an account of the FIB in *National Geographic*, "The offensive against the M23 was arguably the most aggressive military action the UN had undertaken in more than 50 years."[36]

The FIB was controversial within the UN and among international NGOs, who saw it as compromising the UN's neutrality.‡ The FIB's actions against M23—though belated—were a clear victory for the UN. The FIB is currently headquartered in Beni, in the area where the ADF operates. One might reason that the UN's drones would work closely with the FIB. However, Fragasso explains, "we [the drone operators] don't have contact with the military organizations who could be interested in the mission. We have limited point of contact. We don't know who is committing the mission."[37] Johnson, the UN intelligence officer, says that the FIB patrols in similar number and fashion to the "framework" or regular peacekeeping brigades. They have, "relatively the same manpower, same type of equipment," he says. "Every single one of these battalions and brigades out here have the exact same rules of engagement. There is no difference … to me the FIB is not special," says Johnson.

The FIB, Johnson explains, was successful against M23 because M23 acted like a conventional army: "they liked to prepare positions on hilltops … that's not the case with the FRPI."[38] Johnson enunciates the UN's limits: "no foreign force can take down an insurgency. It's got to be a host nation to do it. But we have a lack of governance. No foreign force can establish governance. It's got to be the host national forces that do it. The role of the UN here is to help mitigate the instability, insecurity in the area." At times, as in the FIB's joint offensive against M23, the UN's intervention has been strategically decisive. Even before the creation of the FIB, Indian UN peacekeepers flying Russian-made Mi-35 attack helicopters used them to attack armed groups. The CNDP (the predecessor to M23) tried to take Goma in November 2006 and again several times in the fall of 2008. In both cases, "helicopters aided the ground troops of MONUC and the Congolese army (the FARDC) by determining the exact locations of the rebels and, when necessary, aiming rockets or machine-gun fire directly at them."[39] Walter Dorn writes: "in the crucial test of September–November 2008, [the Mi-35 attack helicopters] proved to be a key enabler to repel aggression. The rebel attack on Goma was thwarted, and the United Nations protected a major population centre, something it had failed to do in other missions. This success served as a lesson of robust peacekeeping."[40]

But such successes are difficult to weigh against failures; thwarting one attack is of little consolation to the victims of a subsequent attack. Frederick Maisha Bifuku, a lawyer and

* The red flags were meant to be waved as an indication that they were allies.

† M23's history is, like that of most Congolese armed group, complicated. The interested reader should consult "From CNDP to M23" (2012), a Rift Valley Institute paper by Jason Stearns, an accessible, authoritative history of M23.

‡ Timo Mueller, a researcher with Human Rights Watch, has compiled a comprehensive and useful reading list on the FIB, available here: http://muellertimo.com/2014/12/18/the-force-intervention-brigade-a-reading-list/

A village in Masisi, North Kivu, a region in the Congo which has seen a great deal of fighting in recent years.

political commentator in Goma, says the idea of surveillance drones is a useful one. However, he asks, "Did these drones become blind when they reached the Congo?"[41] Clugston and his colleagues are far from blind; they are competent and they are well-meaning. However, the disconnect between MONUSCO's good intentions and its actual effectiveness is one reason why the Congolese population perceives it so negatively. According to a poll taken in late 2013 in a joint Harvard-UN Development Programme study, "77 percent of the respondents judge the contribution of MONUSCO to security as being weak to non-existent."[42]

An optimistic take is that the drones, by virtue of the information they create, can goad the UN into more dynamic and effective action. As political scientist Langdon Winner has put it, "If one has access to tools and materials of woodworking, a person can develop the human qualities found in the activities of carpentry."[43] The same holds for institutions. However, as Winner notes, it is rarely clear how strong a particular technology's capacity to shape society is; it is certainly not clear in the case of drones. If drones are to be used effectively by the UN, the information drones gather must be used in conjunction with other sources of information. Whether these other sources are labeled "human intelligence" or "community relations" is in part a matter of attitude; the UN as an institution does a poor job of speaking to local people, however one wants to label such interactions. There are, of course, exceptions to this rule on an individual level. However, as Autesserre writes, "Interveners rarely hold in-depth discussions with ordinary citizens."[44]

Brigadier General Saif Ur Rahman, a Bangladeshi general who is in charge of MONUSCO's Ituri Brigade, says that though the UN is still learning how to use drones, he hopes they will allow the UN to do the same job with fewer soldiers.[45] This is the wrong ambition for the UNs drones. They can make peacekeepers more effective; they can help keep peacekeepers safer. Drones can in principle act as a force multiplier. But MONUSCO—like other peacekeeping missions—has far fewer personnel than are needed to accomplish its stated goals.*

The role of UN peacekeepers has been an evolving one; it is not only in the DRC that the UN has come to play a more proactive role, but also in Mali, the Central African Republic, and Sierra Leone. This is an evolution of which drones are a part, though changes in peacekeeping doctrine are an active area of debate and disagreement within the UN. A 2015 report from a "High-Level Independent Panel on Peace Operations" notes, "In the absence of a peace to keep, peacekeepers are increasingly asked to manage conflict. A rethink of capabilities and concepts is needed, to support these conflict management missions."[46] The panel's recommendations call for "extreme caution" if peacekeepers are to undertake "enforcement tasks," but also say "peacekeeping principles ... must be interpreted flexibly in light of changed circumstances, and not be used as a shield for inaction."

If the UN continues to use drones without effectively analyzing and acting on the information they gather, the drones risk becoming a sort of technological apotheosis of the UN observer—capable of seeing great horrors more systematically than ever before, but unable to do anything about them. Another alternative is that the UN, unable or unwilling to expand its mandate in response to the capabilities drones provide, decides simply to stop using them. Asking "how effective are drones?" is not a terribly useful question. Their utility is a function of the UN's willingness to reconcile what its mandate says on paper—to use all means necessary to protect civilians—with the realities of a recalcitrant Congolese government and the complicated political dynamics among troop-contributing member states. Drones go to the heart of the dilemmas facing the UN as it wrestles with its role as a global arbiter.

* It is not simple, or likely even possible, for the UN to increase the number of peacekeepers somewhere like the DRC. The Congolese government is pressuring the UN to leave entirely; force numbers are a matter of acrimonious political negotiation.

Konstantin Kakaes

The road south from Bunia goes up over bumpy green hills, climbing an escarpment that, on its far side, drops off to the Albertine Rift, the western branch of the Great Rift Valley. After passing a few small waterfalls, it gets high enough to allow one to see Lake Albert sparkle below. In the distance, Uganda comes in and out of view, barely visible through the mist. Villagers push heavily laden bicycles up the hills. The road divides at Bogoro. One branch leads down to the lake and another south to Aveba, where, in January, MONUSCO announced a joint operation with the Congolese army against the FRPI. The road goes first through the Lagabo refugee camp and then through a series of villages that give way to one another without clear boundaries between them: Lagabo, Nombe, Kagaba. Every few miles, Congolese soldiers, posted in ones and twos, watch the road; some are in uniform, and some are not.

A health clinic in Geti, the first major town, treats one to two rape victims a week.[47] The clinic doesn't give information about rapes to the authorities, says Manasse Avuta, a nurse there, because it is confidential. Nurses say fighting has gotten worse lately. They've seen malaria incidence rise, Avuta says, because people sleep in the forest to avoid militia members who come in the night. Munuro Console, another nurse, remembers an attack in early April.[48] Child soldiers, she says, came early in the morning and knocked down the door of a house, cutting a middle-aged woman badly with machetes and injuring a man as well, though he ran away. The soldiers fired their guns, though they did not kill anybody that night. Villagers gathered and shouted, and MONUSCO troops arrived, keeping a distance, she says, of about a hundred meters. "We are dying," she says, "and they are taking pictures." **§**

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CONCLUSION

"If there is a distinctive path that modern technological change has followed, it is that technology goes where it has never been," Langdon Winner, a political scientist, wrote in 1980. The development of drones, surely enough, has followed this progression. As this book chronicles, within a few short years of coalescing as technological artifacts, drones have been deployed to the corners of the world, from the Arctic to the Antarctic, in mountains and in desert valleys below sea level, in cities and above isolated villages.

It is a truism that drone technology is rapidly changing. But this is not the whole truth. Some aspects are changing rapidly; others, such as propellers, are changing slowly, if at all. As a rule, those parts of a drone that have to do with information collection and processing are likely to continue to develop at a brisk pace; the parts that have to do with the physical movement of a drone through the air are also changing, but not as dramatically. Crucial inflection points in the development of drones have come when innovations in microelectronics have enabled innovations in physical movement. This is true of the accelerometer and gyroscope data that make it possible for quadcopters to maintain stability, and of GPS devices that allow drones to navigate from one point in space to another. Another such inflection point may come when the efficiency of photovoltaic cells in converting light to electricity becomes such that even small drones, if light enough in weight, will be able to loiter indefinitely. The intelligence of drones in sensing and avoiding obstacles is, along with that of their cousin, driverless cars, improving rapidly.

All of this means that the amount of information drones can gather has the capacity to grow more quickly than the human ability to take it all in. There is little to be gained by flying drones around willy-nilly. As Mathew Lippincott and Shannon Dosemagen wrote in chapter 2, drones, like any other device, are part of a social system. Because they are new, norms are only now emerging for their use. There is a story in the news almost weekly about an irate neighbor taking potshots at a drone that wandered over his property. As airplanes did before them, drones are forcing us to reconsider the question of who owns the air above our heads. It is unclear at present how profound their impact on daily life will be.

This question hinges in part on whether delivery of physical goods via drone will become commonplace. A number of new initiatives, like Red Line at the Swiss Federal Institute of Technology in Lausanne, propose to deliver payloads in rural Africa using drones. If they succeed, they may reshape the lives of hundreds of millions of people who live hours from basic health services, schools, and markets, cut off from the world by muddy, rutted, often impassable roads.

Large companies like Amazon and Google propose to reshape the rich world's infrastructure with drones delivering packages that are now sent by truck. Many of these cargo initiatives plan on aircraft that will take off vertically and fly horizontally. This is a technically tricky problem to solve. It likely is a necessary hump to be overcome if delivery drones are to prove economically viable. Pure quadcopters lack the needed range and endurance; fixed-wing aircraft that can carry a substantial payload need too much space to take off and land. But if delivery drones succeed, they will likely far outnumber all the other uses of drones put together.

Drones as observers in the sky will remain important for the indefinite future. They will grow easier to operate. The ease of flying and taking pictures can mask the fact that questions concerning how to use those pictures will not get any easier with higher sensor resolutions, better lenses, or cheaper memory.

In an essay on the effect of new technologies, Winner came to the conclusion that the crucial questions are: "How are we to live together? How can we live gracefully and with justice?" These may seem rather generic questions to pose in closing a book on drones. However, the hope expressed in this book is that the information that drones gather can, in some small way, help answer them. §

APPENDIX 1: GLOSSARY

ADF Allied Democratic Forces, an armed group in the Democratic Republic of the Congo.
CCD Charge-coupled device. A digital imaging sensor.
CMOS Complementary metal-oxide semiconductor. A digital imaging sensor.
DRC Democratic Republic of the Congo.
Drone Common term for unmanned or remotely-piloted aircraft
FAA Federal Aviation Administration.
Falco Selex ES Falco, an Italian-made fixed-wing drone.
FDLR Forces démocratiques de libération du Rwanda (Democratic Forces for the Liberation of Rwanda), an armed group present in the eastern DRC.
FLIR Forward-looking infrared.
FRPI Forces de résistance patriotique d'Ituri (Front for Patriotic Resistance of Ituri), an armed group present in the eastern DRC.
GCS Ground control station.
Georectification The act of adjusting an image so that it fits a known coordinate system.
Georeferencing The act of aligning geographic data (such as a map) to a known coordinate system.
Gimbal A mechanism that allows a device, such as a camera, to rotate about one, two, or three axes independently of a body to which it is attached, such as a drone.
GIS Geographic information system. In general terms, a system that is designed to manipulate, store, analyze, and manage spatial and geographic data.
GNSS Global navigation satellite system. The generic term for constellations of satellites that, through sending out synchronized timing signals, allow users to determine their position. These include America's GPS, Russia's GLONASS, China's Baidou, and the European Galileo.
GPS Global Positioning System, a series of satellites developed by the American military to enable users to determine their position.
Ground control points Clearly marked and accurately surveyed locations that can be used as reference points in aerial images.
GSD Ground sample distance. The resolution of an aerial image.
Hexacopter A six-armed multirotor UAV.
Hyperspectral images Images that measure the intensity of light in many narrowly defined bands of wavelength, which allows for automated detection of the composition of objects in the picture.
IMU Inertial measurement unit. A small device commonly found on UAVs that measures changes in speed and rotation using accelerometers and gyroscopes.
Infrared A type of electromagnetic radiation invisible to the human eye (but perceptible in the form of heat) that can be detected with specialized imaging equipment.
ISO A measure of sensitivity to light devised by the International Organisation for Standardization for film and now used for digital sensors as well.
LIDAR Light detection and ranging. A remote sensing technique that measures distance by use of a pulsed laser.
MEMS Microelectromechanical systems. Computer chips that contain small mechanical devices that can measure things such as acceleration or rotation.

MONUC Mission de l'Organisation des Nations Unies en République démocratique du Congo. The previous name for MONUSCO. See below.

MONUSCO Mission de l'Organisation des Nations Unies pour la stabilisation en République démocratique du Congo. The UN peacekeeping mission in the DRC, which has been present since 1999 but until 2010 was known as MONUC.

Multirotor An aircraft with multiple rotors (or propellers).

Nadir In aerial photography, the point on the ground that lies directly below the perspective center of the camera lens; also, images taken from this perspective (i.e., straight down).

NDVI Normalized difference vegetation index. A graphical index of plant health that is commonly applied to remote-sensing data.

Oblique An aerial photograph shot at an angle that is between the horizontal angle and the perpendicular angle. High-oblique photographs show the horizon in the image, while low-oblique photographs do not.

Octocopter An eight-armed multirotor UAV.

Orthomosaic A two-part process in which a number of images are combined together or "stitched" into a single image and also corrected for distortion.

Orthorectification
A process of removing the effects of image perspective and relief effects by using camera model information and elevation data, creating a final image that has a constant scale.

Quadcopter
An aircraft with four rotors (or propellers). The most common multirotor UAV design.

RC Radio-controlled.

RPAS Remotely piloted aircraft systems.

RPAV Remotely piloted aerial vehicles.

RTK Real time kinematic. A technique used to extract more-precise-than-normal position data from global satellite navigation timing signals.

Thermogram A false-color image created from infrared radiation.

Total station A common surveying instrument that combines an electronic distance meter with an electronic theodolite, a device that measures angles.

UAS Unmanned aerial system. Can refer to the entire system, including ground control mechanisms, or to an unmanned aerial vehicle.

UAV Unmanned aerial vehicle.

UHF Ultrahigh frequency.

VHF Very high frequency.

APPENDIX 2:
UAV PREFLIGHT AND POSTFLIGHT CHECKLIST — PRINTABLE

PREFLIGHT

- [ ] Check local regulations, airport proximity, and altitude restrictions before you arrive in the field.
- [ ] When relevant, work with local community members to describe what you will be doing and to answer questions.
- [ ] Ensure a spotter can come to the field site with you.
- [ ] When applicable, create your autonomous mission in the relevant software and perform a simulation.
- [ ] Check the planned flight area for obstacles, animals, and people.
- [ ] Evaluate wind speed, visibility conditions, and potential for inclement weather.
- [ ] Ensure adequate room for the UAV to safely take off and land.
- [ ] Inspect airframe and ensure propellers, engine, gimbal, and camera are attached.
- [ ] Test electrical connections.
- [ ] Check batteries to ensure they are fully charged and functional.
- [ ] Ensure camera or sensor batteries are also fully charged.
- [ ] Check that camera or sensor memory is present and has capacity.
- [ ] Ensure RC and telemetry systems are functioning.
- [ ] Perform brief test flight before starting intended mission.

POSTFLIGHT

- [ ] Power down UAV.
- [ ] Remove and safely store batteries.
- [ ] Check camera or sensor to ensure all required data have been collected.
- [ ] Make logbook entry.

PREFLIGHT CHECKLIST

This is a general checklist describing some best practices before beginning a UAV mission. Each UAV is different, and it is important to tailor your technical preflight checklist to whatever your individual setup requires.

This checklist was adapted from documents produced by the Humanitarian UAV Network,[1] Rob Thompson,[2] and Event38.[3]

BASICS

Practice extensively before you bring your UAV into the field. Learning to fly a UAV, while not difficult, is necessary to carry out useful—and safe—fieldwork. Find an area flight club or a mentor who is willing to train you. Keep a logbook of all your recorded flight hours.

PERMISSION

Before planning a mission or a project, ensure it is legal to fly a UAV in the area you plan to fly. Check national and local laws, and determine whether your mission will take place at the minimum distance away from controlled airspace. Formally request permission from local government and communities before flying over the airspace when possible. Verify what the maximum legal altitude limit is in the area where you are flying.

ENVIRONMENT

Ensure the site is away from large groups of people, utility wires, poles, low-hanging trees, and other obstacles. If possible, walk the site prior to the flight to get a sense of where you will be going. If not, try to evaluate it using existing imagery such as Google Maps.

Ensure there is enough space to safely launch the UAV without endangering yourself or colleagues. Ensure there is an adequate buffer zone between the UAV and potential onlookers.

Select a takeoff site that will permit you to maintain visible line of sight (VLOS) at all times or will ensure that flight beyond VLOS (if permitted by local regulations) can take place without the telemetry connection being obstructed.

SOFTWARE

If you are flying an autonomous mission, use the simulation feature of your software to do a virtual run-through of your flight before you actually take off. Ensure “fail-safe” options are functioning. Make sure you will be taking enough pictures or video to create the planned visual product.

HARDWARE

Ensure you have enough batteries on hand to carry out your planned flights, preferably with spares. Inspect UAV airframe for signs of damage or trouble.

Ensure the propellers are firmly attached to the motor, and that all sensors and batteries are properly fastened. Test all the UAV’s electrical connections, ensuring everything is plugged in and secured.

Ensure that your UAV is communicating with your radio controller. Ensure that all telemetry equipment is functioning properly.

Before embarking on a full mission, power up the UAV and hover at a low altitude to ensure everything is working appropriately.

CAMERA

Test photography equipment to ensure that it is working and firmly mounted to the UAV. Make sure that your camera settings are correctly configured for your mission and that the camera batteries are charged.

Ensure there is enough room on your memory storage medium to record your entire mission. If relevant, be sure to begin recording before you begin flying.

PUBLIC AWARENESS

If you are flying in a populated area, it is important to inform local residents about what will be happening in advance. Local radio, newspapers, fliers, and Internet communities are good ways to distribution information well in advance.

Optimally, meet with community representatives beforehand, and explain the mission, the technology, and why you are there. Try to give something back to the community, including photographs, maps, or perhaps flight training. Involve locals who have prior experience with UAVs.

If local residents express concern over privacy, listen to them. Figure out whether a compromise can be made. Offer to show them how the UAV works and what kind of images it takes. Work to remove identifiable information if requested and if reasonably possible.

INSURANCE

While UAV insurance is a new field, that is no excuse for failing to secure it. Some companies do provide insurance for UAVs, and you should be prepared to assume all liability for your actions. Some air organizations and networks, such as the Humanitarian UAV Network, will not work with operators who have not secured insurance.

IN-FLIGHT

Check local regulations pertaining to VLOS operations. If flight outside VLOS is permitted, ensure the UAV is in communication with the operator. If flight outside VLOS is not permitted, ensure the UAV remains within sight at all times. If possible, bring along a spotter who can keep an eye on the UAV, spot potential obstacles, and deal with warning away or talking to people who may approach you while you fly.

When landing, ensure there are no obstruction hazards, animals, or people in the vicinity of your intended landing location. Pay careful attention to the UAV during the landing process.

POSTFLIGHT

Shut down the UAV and disconnect the batteries. Turn off the transmitter, and power down the camera or sensors. Check the UAV for signs of damage or wear. Secure the aircraft, and ensure it is out of the way of bystanders.

Check the pictures and ensure that the UAV recorded what you set out to record. If not, consider redoing the mission.

Keep logbook entries recording your flight time and what you did.

ENDNOTES

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2 Rob Thompson Jr., "Play It Safe, UAV Operations Checklist For Beginners, Enthusiasts, and Professionals," LinkedIn, June 11, 2014, https://www.linkedin.com/pulse/20140611174837-92630692-play-it-safe-uav-operations-checklist-for-beginners-enthusiasts-and-professionals.

3 Kurt Scudder, "E382 Preflight Checklist," Event38, http://event38.wikispaces.com/E382+Preflight+Checklist.

APPENDIX 3:
ONLINE RESOURCES

New America maintains a database of noteworthy global drone flights at:

http://drones.newamerica.org

intended to showcase many of the civil activities that have been accomplished using drones in recent years.

New America also maintains a database of changing global drone regulations, at:

http://drones.newamerica.org/#regulations

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The drone industry is growing and changing very quickly, and it can be difficult to keep up. In addition to New America's websites, here is a non-exhaustive list of useful UAV websites, in no particular order. Beyond these websites, many user groups devoted to drones operate on Facebook and other social media websites.

DIY Drones
http://diydrones.com
Popular online community devoted to custom-built UAVs. A good source of technical information and advice.

FlightRiot
http://flightriot.com
Online community devoted to open source UAV mapping, including tutorials, downloads, and practical advice.

The Buzzer
http://www.thebuzzer.co/
Informative weekly newsletter devoted to aerial robotics and drones.

SUAS News
http://www.suasnews.com
Popular website that aggregates UAV-related news from across the Internet.

DroneLife
http://dronelife.com
Online drone magazine covering the hobby, regulations, reviews, and the drone business.

DroneGirl
http://thedronegirl.com/
Blog devoted to the drone industry and drone hobby.

MultiRotor Forums
http://multirotorforums.com/forums/
Popular online forum devoted to multirotor aircraft.

FlipBoard Drones Page
https://flipboard.com/topic/drone
A popular aggregator of UAV news.