Overcoming Technological and Policy Challenges to Medical Uses of Unmanned Aerial Vehicles

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ABSTRACT

Unmanned aerial vehicles (UAVs, or "drones") can bring a powerful lifesaving capability to medical situations in which time is critical. Eventually, drones may also bring efficiency and cost savings to nonurgent medical situations. In some places, such as Rwanda and Ghana, UAVs are already saving lives by transporting blood products and other medical supplies across those countries. The United States and other developed countries are exploring potential uses for medical UAVs and conducting experiments accordingly. Techno-optimists envision skies filled with drones executing medical missions, as well as performing more quotidian tasks like delivering packages. The possibilities, indeed, are considerable, but it is important to temper optimism with a sober look at the obstacles that stand between the present and this imagined future. Making full use of UAV technology will require technological advances and regulatory changes to mitigate the risks large-scale drone traffic would impose on America's heavily used airspace. A catastrophic incident (say, the downing of an airliner) could eviscerate public tolerance of the technology, so the challenge for timely deployment is to achieve a high degree of safety without a destructively high level of risk aversion.

JEL codes: H8, O31, O32, O33, R4

Keywords: medicine, medical, healthcare, drone, unmanned aerial vehicle, unmanned aerial system, technology, regulation, innovation, engineering, transportation, communication

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The possibilities are fetching. Futurists envision a world in which unmanned aerial vehicles (UAVs, or "drones") transport blood, surgical supplies, drugs and vaccines, transplantable organs, defibrillators, contraceptives, disaster-relief food and medical supplies, and telemedicine kits.[1] Innovators have completed successful proofs of concept and prototypes for some of these applications. Other applications have already achieved large operational capacity. For instance, the California-based company Zipline has operated a system of medical drones throughout Rwanda since October 2016 and a similar system in Ghana since April 2019. Zipline reported that it had flown 25,094 "lifesaving operations by drone" by December 2019 and that its deliveries account for nearly two-thirds of blood-product deliveries in Rwanda outside the capital city.[2]

But unlike Rwanda and Ghana, whose skies are relatively uncluttered, the United States and other high-income countries enjoy (or suffer) heavy traffic in their airspace. In such an environment, current UAV technologies are insufficiently safe, durable, and reliable. Were a drone to collide with and down a civilian airplane or a news helicopter, the accident could undermine the future of the industry and eviscerate all its potential benefits. Therefore, before drones can play a significant role in healthcare in the United States, technology needs to improve and the way airspace is regulated needs to change.

In the United States and other developed countries, there are multiple situations in which UAVs could be useful. The United States, for example, has vast rural areas where ground transportation is slow and costly and where manned air transportation is likely to be prohibitively costly. Urban areas can be plagued by traffic jams—a serious problem when, say, a patient with a rare blood type is hemorrhaging and needs a transfusion. When weather conditions such as ice,

1. James C. Rosser et al., "Surgical and Medical Applications of Drones: A Comprehensive Review," *Journal of the Society of Laparoendoscopic Surgeons* 22, no. 3 (2018).
2. Zipline website, accessed December 11, 2019, https://flyzipline.com/.

fog, or wind make travel hazardous, it can be risky, difficult, or even impossible for human couriers to make urgently needed deliveries. And after natural disasters, normal transportation routes are often shut down.

The mission of upgrading UAV technology to fit comfortably into the airspace of the United States or Western Europe poses significant challenges—most of them involving large sums of money:

- UAVs must be able to maintain constant communication with ground operators. This is even more important for drones than for airplanes, since there is no pilot on board to guide the vehicle in case of a communication lapse. Maintaining such communication almost certainly requires satellite-based communication systems, because there are directional limitations for cellular signals at higher altitudes and cellular service is not proliferated to many remote areas where the drones would operate.
- UAVs must have enormously reliable sense-and-avoid computing capabilities, preventing them from colliding with airplanes and other airborne vehicles, as well as with buildings, trees, hills and mountains, electrical wires, and humans.
- UAVs must also be resistant to interference by hackers and to other unauthorized uses. For instance, there are security concerns related to the fact that most drones today use hardware and software produced in the People's Republic of China, and thus they could potentially be used by the government of China for nefarious activity.
- Given the immense distances within the United States, effective medical UAVs must be capable of flying beyond the visual line of sight (BVLOS). In other words, the horizon cannot be the limit of a drone's reach—as is generally the case at present, owing to legal restrictions.
- Long-distance flight will likely require the development of powerful, reliable, lightweight internal combustion engines. (Today's UAVs are generally battery powered.) The effort to miniaturize such engines will be costly.
- A safe, reliable system of medical UAVs will also require extensive ground-based infrastructure—buildings, equipment, and personnel. As we will discuss later, the military has found that UAVs can require more personnel than airplanes.

Heavy use of medical drones will likely require a major reconfiguration of the architecture of US airspace, the structure of which was established in the 1950s. It is difficult to shoehorn a new class of vehicle—and many individual machines—into that infrastructure. This and other issues will be discussed below. The following sections explain the terminology of UAVs, the motivations for using UAVs in healthcare, the technical challenges ahead, and the public policy issues that will need to be sorted out.

TERMINOLOGY

This article generally uses the terms *unmanned aerial vehicle* and *drone* interchangeably, but such usage is somewhat controversial. In civilian circles today, the word *drone* is used for almost all unmanned aerial vehicles, and the term may also incorporate the support systems for those vehicles. Military terminology is a bit more nuanced and precise.

In present-day military terminology, *unmanned aerial vehicle* (UAV) describes the flying vehicle itself. The *unmanned aerial system* (UAS) includes the UAV plus the infrastructure required to operate the UAV. This infrastructure includes the ground control station, where the pilot typically sits while operating the UAV. The UAS also includes the software, hardware, and communications links that influence the integrity, safety, and efficiency of the UAV.

In a sense, the word *drone* has come full circle over the past four decades. In the late 1970s, drones were remotely controlled aerial vehicles used by military aviation for target practice. As the mission of such vehicles expanded, the term *remote piloted vehicle* (RPV) was adopted to describe vehicles used for purposes other than target practice. By the late 1990s, the term RPV fell from favor and was replaced by UAV and UAS.

The value of UAVs became clear to the intelligence community and the Department of Defense early in the process known as the Global War on Terror. As UAS adoption quickly grew, so did the budget for the development and procurement of this game-changing technology. Some senior military leaders responsible for these budgetary changes objected to the word "unmanned" because, counterintuitively, the more sophisticated UAS projects required more personnel than did manned vehicles (e.g., airplanes). Such personnel included those assisting in launch and vehicle recovery, maintenance workers, programmers, and other individuals with specialized duties. There was a push to revert to terms such as RPV, but that initiative never took root. So the terms UAV and UAS remain.

As the commercial world developed UAV technology and made it affordable for individual consumers, the term *drone* returned. The media began to use it, describing military air strikes using UAVs as "drone strikes" because the description was readily understood. So, though the term *drone* is not necessarily popular in the UAS community—military or civilian—the word stuck and quickly entered the popular lexicon.

WHY MEDICAL DRONES?

In healthcare-related media, headlines and taglines reflect a breathless anticipation of the uses of drones in medical care: "Drones Hold Promise to Save Lives and Improve Rural Healthcare."[3] "Leo A Daly's Miami studio envisions a drone-powered hospital that enhances resilience to natural disasters."[4] "Medical Drones Market Expects to Reach Almost $400M by 2025."[5] "The Trick to Achieving Universal Health Care? Drones."[6] "Drones in Medicine—the Rise of the Machines: This Is a Medical Kitty Hawk Moment."[7] "9 Drones That Will Revolutionise Healthcare."[8] "Your Medical Supplies Could Soon Arrive by Drone."[9] "Medical Drones Will Thrive in Healthcare: A Safe Road to Health."[10] "How Drones Are Bringing New Hope in Health Sector."[11] The authors of this paper are not immune to the enthusiasm: "Drones Delivering Medical Supplies and More Can Help Save American Lives."[12] "The Promise of Medical Drones."[13]

Drones have already begun to play important roles in healthcare, and it's clear that their importance will increase both abroad and in the United States. This paper has already referred to the medical supply delivery systems set up in Rwanda and Ghana.[14] In southern Africa, Malawi has been working with inter-

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3. "Drones Hold Promise to Save Lives and Improve Rural Healthcare," *Modern Healthcare*, June 9, 2018.
4. John Caulfield, "The Healthcare Sector Is Turning to Drones to Supplement Medical Services," *Building Design & Construction*, May 3, 2019.
5. "Medical Drones Market Expects to Reach Almost $400M by 2025," *AZ Business Magazine*, July 6, 2019.
6. Andrew Nusca, "The Trick to Achieving Universal Health Care? Drones," *Fortune*, April 2, 2019.
7. Manohari Balasingam, "Drones in Medicine—the Rise of the Machines: This Is a Medical Kitty Hawk Moment," *International Journal of Clinical Practice*, August 29, 2017.
8. Nicholas Dragolea, "9 Drones That Will Revolutionise Healthcare," *Doctopreneurs*, August 15, 2019.
9. Jack Guy, "Your Medical Supplies Could Soon Arrive by Drone," *CNN*, December 21, 2018.
10. "Medical Drones Will Thrive in Healthcare: A Safe Road to Health," *Medical Futurist*, January 12, 2017.
11. Kushagra Shukla, "How Drones Are Bringing New Hope in Health Sector," *Geospatial World*, November 9, 2018.
12. Robert Graboyes and Darcy Nikol Bryan, "Drones Delivering Medical Supplies and More Can Help Save American Lives," *STAT*, January 18, 2019.
13. Robert Graboyes, Darcy Nikol Bryan, and Chad Reese, "The Promise of Medical Drones," January 22, 2019, in *Mercatus Policy Download*, produced by the Mercatus Center at George Mason University, podcast, MP3 audio, 30:39.
14. Aryn Baker, "The American Drones Saving Lives in Rwanda," *Time*, July 20, 2017.

national agencies to develop the capacity to use drones for disaster preparedness and disaster response.[15] In the United States, universities in North Carolina and Maryland are experimenting with drones for rapid delivery of urgently needed medical supplies.[16]

It is tempting to view UAVs as a cost-saving measure. But while they might eventually cut costs, for the present, the strongest argument for medical UAVs appears to be humanitarian—they provide the ability to get blood, drugs, defibrillators, and other lifesaving cargo to patients in situations where time is extraordinarily critical.

Medical UAVs in Developing Countries

Medical applications of UAVs are nascent in the United States and other developed countries. But for several years, the preeminent testing grounds for such applications have been in countries of the developing world—Ghana, India, Rwanda, Vanuatu, and so forth. This is logical, given at least four conditions that prevail in these developing countries. First, poor road conditions can make ground transportation particularly difficult. Second, air traffic is relatively light, so the odds of drones colliding with airplanes or helicopters is relatively low. Third, in many developing countries, there is a general air of enthusiasm about technology as a means of leapfrogging over past infrastructure inadequacies. And fourth, the quality of healthcare is sufficiently poor and the resources sufficiently slim that these countries appear more willing to accept risk and novelty in the delivery of care.

Rwanda was the first country to adopt a nationwide system of medical drones, in partnership with Zipline.[17] Zipline has documented the lifesaving impact of its operations: "Our drones fly over remote mountains, rivers, and washed-out roads. They require no local infrastructure to serve communities. . . . Within 30 minutes, medical supplies are delivered from the sky by parachute. Recipients don't interact with the drone itself."[18] In one case, a woman named Alice Mutimiutugye was bleeding severely during childbirth. Delivery of blood by road would have taken many hours. A drone, however, reached her around 30 minutes after the clinic had placed its order. Mutimiutugye and her baby survived.[19]

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15. Miriam McNabb, "Drones for Good: Disaster Management and Humanitarian Aid in Malawi," *Dronelife*, September 21, 2017.
16. A. J. Heightman, "Care from the Air," *Journal of Emergency Medical Services*, July 25, 2019.
17. Baker, "American Drones Saving Lives."
18. Zipline website, accessed August 1, 2019, https://flyzipline.com.
19. Paul Nuki, "Pointing the Way: How Medical Drones Are Saving Lives in Africa," *Telegraph*, February 16, 2018.

RAND researcher Shira Efron notes, "Drones are also seen as a possible solution to infrastructure problems, especially in Africa where air transportation could help meet the challenges posed by poor or non-existent road and rail networks. In fact, experts believe that drones could account for 10 percent to 15 percent of Africa's transport sector in the next decade."[20] South Africa has passed legislation to train and license drone pilots.[21] Malawi is operating a drone testing corridor.[22] Tanzania has initiated medical drone deliveries in a pilot project with delivery service DHL, German UAV manufacturer Wingcopter, and a corporation working on behalf of the German Federal Ministry for Economic Cooperation and Development.[23] And, as noted above, Zipline began operating in Ghana in 2019.[24] In the Democratic Republic of Congo, vaccines were recently delivered by drone for the first time.[25]

The Pacific nation of Vanuatu, in partnership with the United Nations Children's Fund (UNICEF), Australia's Swoop Aero, and Germany's Wingcopter, has begun using drones to deliver vaccines to remote islands.[26] UNICEF notes that vaccines are highly sensitive to temperature, so rapid delivery by drone reduces the difficulty of delivering them to remote islands.[27] In the Philippines, the Red Cross, in partnership with Nokia and PLDT wireless unit Smart Communications, has been testing UAV services for the delivery of medical and other supplies in disaster areas.[28] In India, several emergency-medicine physicians ran an experiment with medical drones; functions included disaster-area reconnaissance, supervision of patient transfers, cordoning a disaster site, basic life support, transport of samples, and intrahospital transport of medicine.[29]

The Republic of Kazakhstan and UNICEF have established a drone testing corridor for experimentation in areas of emergency response.[30] UNICEF is

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20. Shira Efron, "Drones Could Deliver Change to Africa," *RAND Blog*, November 1, 2017.
21. Jake Bright and Samantha Stein, "African Experiments with Drone Technologies Could Leapfrog Decades of Infrastructure Neglect," *TechCrunch*, September 16, 2018.
22. Bright and Stein, "African Experiments with Drone Technologies."
23. Deborah Kaplan, "How Medical Drones Help Save Lives in Tanzania," *DHL*, June 1, 2019.
24. Jake Bright, "Drone Delivery Startup Zipline Launches UAV Medical Program in Ghana," *TechCrunch*, April 24, 2019.
25. Tod Perry, "Villagers Rejoice as They Receive the First Vaccines Ever Delivered via Drone in the Congo," *Good*, September 11, 2019.
26. "Vanuatu Uses Drones to Deliver Vaccines to Remote Island," *BBC News*, December 19, 2018.
27. "Child Given World's First Drone-Delivered Vaccine in Vanuatu," UNICEF, December 18, 2018.
28. "Philippine Red Cross, Smart, Nokia Test Use of Drones in Disaster Response," *Manila Standard*, August 17, 2019.
29. Subhan Imron, Ghazi Syed Safiuddin, and Nabi Syed, "Use of Drones (Unmanned Aerial Vehicles) for Supporting Emergency Medical Services in India," *Apollo Hospital Group* 16, no. 1 (2019).
30. "Drone Testing Corridors Established in Kazakhstan," UNICEF, October 22, 2018.

also involved in UAV programs in other countries, including Ghana and Malawi as well as Vanuatu; the organization's website says that "unmanned aerial vehicles, or 'drone'-based technologies and services are demonstrating the ability to deliver life-saving materials, and in so doing, generate substantial social benefits."[31]

Medical UAVs in Developed Countries

The *Economist* reported in June 2019 that drone deliveries were "no longer just in Africa, but in Europe and America, too"; the article mentions Rwanda, Bhutan, and Papua New Guinea, but also Switzerland and North Carolina.[32] Sweden has experimented with delivering external defibrillators to heart attack victims; a small 2017 test showed drones arriving up to 17 minutes sooner than emergency medical technicians.[33] Studies are underway on how to optimize flight patterns for delivering defibrillators and similar cargo.[34] The US Marines have experimented with using drones to carry blood supplies across battlefields; they are using the same Zipline systems used in Rwanda and Ghana.[35]

In the United States, the most important medical applications of UAVs thus far have likely been in the area of disaster relief.[36] Puerto Rico, ravaged by Hurricane Maria in 2017, has since been experimenting with drone-delivered medical supplies.[37] In 2019, after tornadoes in Alabama and Ohio, UAVs with thermal energy cameras were sent aloft to hunt for storm victims, living and dead.[38]

But experiments are ongoing across the United States in nondisaster settings as well. The year 2015 saw the first UAV delivery of drugs approved by the Federal Aviation Administration (FAA). The drugs were delivered to a pop-up

31. "Drones: Addressing Transport, Connectivity, and Better Medical Preparedness," UNICEF, October 1, 2019.
32. "Drone Deliveries Are Advancing in Health Care: No Longer Just in Africa, but in Europe and America Too," *Economist*, June 11, 2019.
33. Tom Sullivan, "Drones Beat EMS Teams to Heart Attack Victims in Test," *Healthcare IT News*, June 15, 2017.
34. Aaron Pulver, Ran Wei, and Clay Mann, "Locating AED Enabled Medical Drones to Enhance Cardiac Arrest Response Times," *Prehospital Emergency Care*, February 6, 2016.
35. Patrick Tucker, "US Marines Try Using Drones to Bring Blood to Battle," *Defense One*, October 22, 2019.
36. Matthew Parnofiello, "Drones Fly In to Aid Public Safety, Offer Disaster Relief," *StateTech*, March 14, 2018.
37. "Puerto Rico Piloting Drones to Deliver Emergency Medical Supplies," *Healthcare IT News*, September 7, 2018.
38. Bryn Caswell, "Thermal Energy Drones Saving Lives in Alabama Tornado Aftermath and the Miami Valley," *Dayton 24/7 Now*, March 4, 2019.

clinic in Wise County, Virginia, operated by the charitable organization Remote Area Medical.[39] Flirtey, the drone company that operated the mission, has been conducting an FAA-sanctioned experiment in the vicinity of Raleigh, North Carolina, with the help of its partners (including UPS and the Wake Medical Center [WakeMed]). As of March 2019, Flirtey UAVs were delivering medical samples around the Raleigh area.[40]

In fall 2019, the FAA granted approval to UPS to establish the first nationwide UAV airline to deliver medical supplies. This certification extends the services first tested at WakeMed.[41] A few months earlier, Alphabet Inc. (the parent company of Google) was authorized to deliver parcels via drone in the vicinity of Blacksburg, Virginia.[42]

In another FAA-authorized experiment, Flirtey has tested defibrillator and package deliveries around Reno, Nevada.[43] Meanwhile, in California, Stanford Blood Center and the city of Palo Alto, working with Switzerland's Matternet, have been seeking to initiate UAV delivery of blood supplies.[44]

The most ambitious medical UAV mission to date in the United States occurred in Baltimore on April 19, 2019. Physicians flew a donor kidney destined for a transplant patient 2.6 miles across the city. The trip took 10 minutes, as opposed to the 15–20 minutes it would have taken by car.[45]

The Humanitarian Imperative for Medical UAVs

UASs offer a unique opportunity for emergency responders to react to community disasters, traumas, and other life-threatening events in a timely and effective manner. Accurate information, situational awareness, and reliable communica-

39. David Crigger, "Drones Deliver Supplies to Remote Area Medical Clinic," *Richmond Times-Dispatch*, July 17, 2015. For video of the mission, see Virginia Tech, Flirtey, and Remote Area Medical, "Historic Medicine Delivery via Drone," YouTube video, 4:14, posted July 23, 2015, by Remote Area Medical, https://www.youtube.com/watch?v=KoKQF_Tizg4.
40. Marrian Zhou, "UPS Using Drones to Zip Medical Samples around North Carolina: Drone Deliveries Avoid Road Delays, Increase Efficiency and Lower Costs," *CNET*, March 27, 2019.
41. Brandi Vincent, "FAA Certifies UPS to Operate Nation's First Drone-Delivery Airline," *Nextgov*, October 4, 2019.
42. Andy Pasztor, "Google Wins First FAA Approval for Regular Drone Delivery of Consumer Items," *Wall Street Journal*, April 23, 2019.
43. "Flirtey Granted Permission to Conduct BVLOS UAS Delivery Flights under UAS IPP," *AUVSI News* (Association for Unmanned Vehicle Systems International), March 11, 2019.
44. Janine DelaVega, "Drones May Be Used to Fly Blood to Hospitals in Palo Alto," *ABC 7 News*, December 29, 2017.
45. Meredith Cohn, "University of Maryland Medical Center Transplants First Drone-Delivered Organ," *Baltimore Sun*, April 26, 2019.

tion are cornerstones for increasing the chances of survival in any emergency. In a recent American Red Cross report, *Drones for Disaster Response and Relief Operations*,[46] UASs are portrayed as one of the most powerful and promising new technologies for search and rescue. UAVs can provide reconnaissance support, create high-resolution maps, locate people in need of emergency care, deliver lifesaving medical supplies, and function as an ad hoc communications infrastructure to connect mobile devices to the nearest radio access network.[47] As mentioned earlier, military researchers are exploring the use of drones in the practice of battlefield medicine.[48]

The potential for saving lives makes the effort to integrate UASs into the national airspace worth the challenges inherent in using and developing an evolving technology. Headlines in popular media inspire: "Drone Saves Two Australian Swimmers in World First."[49] "Ambulance Drone Could Deliver Life-Saving Care in Under a Minute."[50] "Drone-Powered 'Uber for Blood' Is Delivering Life-Saving Medical Supplies in Africa."[51] "Drones Rescued More Than 65 People in the Last Year."[52]

A clear example of the importance of timely emergency medical responses is the poor survival rates associated with out-of-hospital cardiac arrest (OHCA).[53] Under the current system, only 1 to 5 percent of such patients survive to hospital discharge. The American Heart Association has promoted the "Chain of Survival"—the implementation of a series of steps that result in improved survival statistics following sudden cardiac arrest.[54] Integral to this chain is the early use of automated external defibrillators (AEDs).

Defibrillation performed by witnesses immediately after episodes of ventricular fibrillation results in survival rates greater than 90 percent. However,

46. Measure and American Red Cross, *Drones for Disaster Response and Relief Operations*, April 2015.
47. Milan Erdelj et al., "Help from the Sky: Leveraging UAVs for Disaster Management," *IEEE Pervasive Computing* 16, no. 1 (January–March 2017).
48. Jonathan Braun et al., "The Promising Future of Drones in Prehospital Medical Care and Its Application to Battlefield Medicine," *Journal of Trauma and Acute Care Surgery*, July 1, 2019.
49. "Drone Saves Two Australian Swimmers in World First," *BBC News*, January 18, 2018.
50. Teodora Zareva, "Ambulance Drone Could Deliver Life-Saving Care in Under a Minute," *BigThink*, November 4, 2014.
51. Mike Wehner, "Drone-Powered 'Uber for Blood' Is Delivering Life-Saving Medical Supplies in Africa," *BGR*, January 2, 2018.
52. Malek Murison, "DJI: Drones Rescued More Than 65 People in the Last Year," *Dronelife*, April 30, 2018.
53. John P. Marenco et al., "Improving Survival from Sudden Cardiac Arrest: The Role of the Automated External Defibrillator," *JAMA* 285, no. 9 (March 2001).
54. Richard O. Cummins et al., "Improving Survival from Sudden Cardiac Arrest: The Chain of Survival Concept," *Circulation* 83 (May 1991).

each minute of delay in reversing ventricular fibrillation leads to a nearly 10 percent reduction in the chance of survival.[55] Many rural and densely populated urban communities continue to have poor OHCA survival rates as a result of longer response times from emergency personnel, owing to either remote locations or heavy traffic.[56]

The American Heart Association has promoted public-access defibrillation as a means of improving OHCA survival through the use of layperson responders. AEDs used by nonmedical personnel have been found to be safe and effective. Sweden took this approach a step further and used UAVs to transport AEDs to the site of OHCA cases before the arrival of emergency medical services. Researchers found that in an urban environment, the UAV arrived before medical personnel in 32 percent of cases, with a mean time saved of 1.5 minutes. In rural environments, the drone arrived before medical personnel in 93 percent of cases, with a mean time saved of 19 minutes.[57]

In 2014, Delft University of Technology in the Netherlands announced the development of an "ambulance drone" that is equipped with an AED and can fly at speeds of up to 100 kilometers per hour.[58] This UAV is designed to be rapidly dispatched and fly directly to the OHCA victim's vicinity through use of a bystander's cell phone GPS. The dispatcher can then direct bystanders to use the AED on the patient through real-time video. In the future, GPS may not be necessary. New computer vision and artificial intelligence learning algorithms have been tested to navigate drones in restricted environments and areas where GPS signals do not exist.[59]

Other lifesaving applications of UASs have been shown. In Rwanda, the delivery time for blood and critical medications in remote regions has dropped from four hours to an average of half an hour.[60] Timely arrival of blood products reduces maternal deaths from postpartum hemorrhage, while antimalarial medications prolong lives.

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55. Marenco et al., "Improving Survival."
56. Gary Lombardi et al., "Outcomes of Out-of-Hospital Cardiac Arrests in New York City: The Pre-hospital Arrest Survival Evaluation (PHASE) Study," *JAMA* 271, no. 9 (March 1994).
57. Andreas Claesson et al., "Unmanned Aerial Vehicles (Drones) in Out-of-Hospital-Cardiac-Arrest," *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine* 24 (October 2016).
58. Larry Husten, "Grad Student Invents Flying Ambulance Drone to Deliver Emergency Shocks," *Forbes*, October 29, 2014.
59. Diego A. Mercado, Pedro Castillo, and Rogelio Lozano, "Quadrotor's Trajectory Tracking Control Using Monocular Vision Navigation" (paper presented at 2015 International Conference on Unmanned Aircraft Systems, Denver, CO, June 9–12, 2015).
60. Karen McVeigh, "'Uber for Blood': How Rwandan Delivery Robots Are Saving Lives," *Guardian*, January 2, 2018.

It is important to recognize that many of the same conditions that exist in underdeveloped nations are found in certain parts of rural America. Some residents of the US-Mexico border area and rural Appalachia still live without running water or electricity.[61] No matter where they reside, however, rural Americans are far more likely than urban residents to face healthcare challenges and disparities. Two-thirds of rural counties have poverty rates at or above the national average of 14.4 percent.[62] Emergency response times are often 60 minutes or more.[63] Compared with women in urban areas, rural women have less access to healthcare and experience poorer health outcomes.[64] More than half of all US rural counties do not have hospital obstetric services.[65]

As was mentioned earlier, four conditions of an area make utilization of UASs in healthcare attractive: poor road conditions, light air traffic, enthusiasm for new technology to overcome infrastructure barriers, and resource scarcity that spurs the acceptance of risk and novelty in healthcare delivery. All of these criteria are met in the rural United States. Geographic distance is a large factor in access to healthcare in these regions, with roads often unreliable and healthcare centers often more than an hour away. Class G airspace is by definition uncontrolled and enables the most leeway for unmanned systems. Much of rural airspace not designated for military use can be described as Class G. Many states are already actively researching the use of drones for healthcare in rural areas, and there is significant enthusiasm for the technology.[66]

TECHNICAL CHALLENGES

As the use of UASs expands, the vehicles' payload capacity and range must increase, and for quite some time, that will mean increased costs. In the short to medium term, costs will likely rise dramatically in order to increase safety and

61. Peter J. Hotez, "Neglected Infections of Poverty in the United States of America," *PLOS Neglected Tropical Diseases* 2, no. 6 (2008); Nelda Mier et al., "Health-Related Quality of Life among Mexican Americans Living in Colonias at the Texas-Mexico Border," *Social Science & Medicine* 66, no. 8 (April 2008).
62. Bill Bishop, "U.S. Recession Hikes Rate of Rural Poverty," *Daily Yonder*, January 31, 2012.
63. Darcy Nikol Bryan, "47 CFR Part 54: Promoting Telehealth for Low-Income Customers" (Public Interest Comment, Mercatus Center at George Mason University, Arlington, VA, August 26, 2019).
64. American College of Obstetricians and Gynecologists, "Health Disparities in Rural Women" (ACOG Committee Opinion No. 586), *Obstetrics and Gynecology* 123 (2014).
65. Peiyin Hung et al., "Access to Obstetric Services in Rural Counties Still Declining, with 9 Percent Losing Services, 2004–14," *Health Affairs* 36, no. 9 (2017).
66. Allee Mead, "The Sky's the Limit: Potential of Drone Usage in Rural Healthcare," *Rural Health Info*, April 5, 2017.

reliability. UASs will require advanced object detection capabilities, allowing drones to autonomously avoid other aircraft and obstacles such as buildings, trees, and hills. And they will have to do so with little margin for error.

Recent drone-related accidents and fears of accidents underscore the urgency of developing this capability. For example, London's Gatwick Airport was shut down between December 19 and 21, 2018, because of the potential presence of drones.[67] In July 2019, a police helicopter in Columbus, Ohio, was forced to land after nearly striking a drone.[68] In September 2018, a commercial drone deployed to examine a broken high-rise window in San Francisco crashed to the ground, nearly striking pedestrians.[69] Climate activists have threatened to use drones to shut down Heathrow Airport in London.[70] Drug traffickers have carried illicit drugs across borders using drones. In Nigeria, the terrorist group Boko Haram has used drones to attack federal military forces.[71] In the Middle East, Iran's allies in Saudi Arabia allegedly attacked Saudi oil facilities using drones (though the actual damage to facilities was done by missiles), and Israel allegedly brought down hostile drones over Syria.[72] And on the topic of less global dangers, *Popular Mechanics* asked the question, "What Happens When a Drone Crashes into Your Face?"[73]

Public confidence in flying machines can be shattered relatively easily. In 1937, when enthusiasm for dirigibles was already on the wane, the fiery crash of the *Hindenburg*—reported live on the radio and filmed as it happened—effectively ended public tolerance for that technology.[74] (The *Graf Zeppelin*, carrying passengers from Brazil to Germany, landed the next day; its flight was the final international airship passenger flight.)[75]

Sense-and-avoid technology will require small, powerful supercomputing modules. The good news is that such devices are continually getting smaller. Their widespread use in many commercial applications will help lower costs and

67. Feargus O'Sullivan, "Who Keeps Buzzing London's Airports with Drones?," *City Lab*, January 9, 2019.
68. "Columbus Police Helicopter Forced to Land Due to Drone; Homeland Security Investigating," *NBC4i*, July 9, 2019.
69. "Drone Crashes in San Francisco during Building Inspection," *JDSupra*, September 20, 2018.
70. "Extinction Rebellion Postpone Heathrow Drone Protest," *BBC News*, June 16, 2019.
71. Dionne Searcey, "Boko Haram Is Back. With Better Drones," *New York Times*, September 13, 2019.
72. Jon Gambrell, Josef Federman, and Zeina Karam, "Israel Attacks Drones in Syria: A Pattern of U.S.-Iran Tensions," *Christian Science Monitor*, August 26, 2019.
73. Eric Tegler, "What Happens When a Drone Crashes into Your Face?," *Popular Mechanics*, August 22, 2019.
74. Suzanne Deffree, "Hindenburg Disaster Ends Airship Era, May 6, 1937," *EDN Network*, May 6, 2019.
75. Airships.net, "Graf Zeppelin History," accessed October 1, 2019, https://www.airships.net/lz127-graf-zeppelin/history/.

speed up adoption cycles. Tech company NVIDIA has released a high-powered processor that can be used to control drones and other devices.[76] NVIDIA's Jetson Nano processor offers artificial intelligence capabilities in a smaller, lighter package.[77] Graphics processing units also add to the potential power of UASs.[78] Such systems will eventually provide small, affordable drones with the computing power necessary for real-time, large-dataset processing—a necessary capability for advanced autonomy.

Carrying more weight and flying farther requires larger, more expensive, more technologically advanced systems. For safety reasons, the vehicles will have to aspire to positive communication at all times—a requirement that becomes considerably more challenging when flying BVLOS, the current legal limit for most drone flights in the United States. Larger UAS capability will require satellite communications or some other form of BVLOS architecture for communications with a ground operator. In some cases, safety and efficiency will entail heavy data flows, such as live video. This capability would be critical in an area struck by a natural disaster, for example.

There is progress on this front. America's first FAA-approved BVLOS flight under the agency's Small UAS Rule (to be discussed later) was conducted by a team led by the University of Alaska Fairbanks.[79] That flight could be the precursor to UAS monitoring of pipelines and other infrastructure.

One of the challenges of drones is the sheer volume of data that must be processed and transmitted—essential to preserving the cargo and preventing the drone itself from becoming a hazard.[80] Commercial communication protocols, such as cellular and Wi-Fi, are often not viable. These communication protocols and associated hardware were designed and built to communicate with devices on the ground. Cell towers' antennae are generally pointed at the ground. (Airline passengers who fail to switch their devices to airplane mode often lose cellular coverage soon after takeoff.) Wi-Fi has a short operating radius, as cell phone owners learn when they exit their homes. Wi-Fi and Bluetooth waveforms and devices are not built for communication over long distances.

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76. Roland Moore-Colyer, "Nvidia's Jetson AGX Xavier Will Power Everything from Drones to Robots," *Inquirer*, December 13, 2018.
77. Jim McGregor, "Nvidia's Jetson Nano Puts AI in the Palm of Your Hand," *Forbes*, August 1, 2018.
78. Ayushi Bajpai, "Graphic Processing Unit Market to Reach $151.7 Billion Globally by 2022," *Allied Market Research*, December 1, 2016.
79. Sara Tewksbury, "UAF Led Team Conducts First Unmanned Aircraft Beyond Line of Sight Flight in the Country," *NBC Affiliate*, August 2, 2019.
80. Celia Luterbacher, "How Drones Are Transforming Humanitarian Aid," *Swiss Info*, June 5, 2018.

BVLOS hardware will increase not only the initial cost of the UAS but also the continual operating costs. This is because there are expenses associated with buying or renting time on satellites, also referred to as *airtime*.

Another cost implication relates to engines. Reliable, low-horsepower gas engines are hard to find. Electrical engines are not suitable for the larger aerial vehicles that will be required to carry larger payloads and fly longer distances. Batteries last a lot longer than they did 20 years ago, and that is primarily due to new chemistries. However, the energy density in today's batteries still presents challenges for drones. The problem parallels the difficulty of making powerful, reliable, durable batteries for automobiles and devising an infrastructure for recharging them economically.[81] Long-range flight is especially problematic.[82] The problem of battery limitations has sparked discussions about potential solutions to ensure that drones can succeed in commercial markets.

Adding more batteries to the vehicles is not a viable solution, because batteries add excessive weight. There has been a significant amount of research into the use of fuel cells; while this technology holds great promise for the future, the material solutions are not available just yet. For UAVs, the challenge does not lie simply in building a small, low-weight battery with higher energy density. The chemistry must also be safe and transportable. There are some options available, but today's fuel cells are too costly or too fraught with technical problems to provide a viable solution.[83]

The lack of reliable low-horsepower engines is an economic problem. The cost associated with a robust, reliable low-horsepower engine would be far too expensive for recreational users. Even demand by the US military was insufficient for engine manufactures to invest the tens of millions of dollars necessary for developing the reliability and power required. The bottom line is that reliability is expensive.[84]

Speed and endurance (maximum time aloft) will always be important considerations in the design of UAVs, and both depend on many variables, including the weight and aerodynamic design of the vehicle. The power source for flight is an important consideration, because it is often the largest (or close to the largest)

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81. Kaiqing Zhanga et al., "Dynamic Operations and Pricing of Electric Unmanned Aerial Vehicle Systems and Power Networks," *Transportation Research Part C*, September 9, 2017.
82. Donkyu Baek et al., "Battery-Aware Operation Range Estimation for Terrestrial and Aerial Electric Vehicles," *IEEE Transactions on Vehicular Technology* 68, no. 6 (June 2019).
83. J. Dutczak, "Issues Related to Fuel Cells Application to Small Drones Propulsion," *IOP Conference Series: Materials Science and Engineering* 421, no. 4 (October 2018).
84. Lee Teschler, "Reliability Concerns Drive UAV Propulsion Technologies," *Design World*, July 22, 2016.

contributor to weight and provides the power to fly at required speeds. In addition, fuel efficiency will greatly contribute to endurance.

Let's consider a battery-powered drone. Zipline, the company operating Rwanda's medical delivery system, uses fixed-wing drones weighing around 45 pounds. The battery accounts for almost half the total weight of the vehicle. The drone carries around 3.5 pounds of payload and can remain aloft for at least two hours. Smaller drone engines, such as the Northwest 44 Multi-Fuel engine, power UAVs weighing from 40 to 75 pounds; speed depends on the design of the particular aircraft. Some systems with these engines can fly at speeds up to 90 miles per hour.[85]

With larger systems, innovators have the opportunity to leverage engines that are already used in manned aerial vehicles. The military's well-known MQ-1B Predator uses a Rotax 914 engine.[86] This aircraft can fly at speeds around 135 miles per hour, with a range of up to 770 miles. The same engine is also used in manned aircraft.[87]

As a general rule, the bigger the engine, the greater the power. But other design factors will influence speed and endurance, and the total weight of the aircraft affects required takeoff and recovery methods. The power source is a large contributor to overall weight, adding to the complexity of selecting the right engine. Multi-rotor UAVs are attractive because of their vertical takeoff capabilities and their ability to hover—however, because of the energy they require (as compared to most fixed-wing systems), the multi-rotor design falls short.

Engine reliability will be heavily scrutinized by agencies like the FAA before UASs are allowed to fly over populated areas. There is also something of a chicken-and-egg problem here: Sufficient demand needs to be felt in order for industry to invest heavily in low-horsepower engines that approach the reliability of engines on manned aircraft, but building demand for such engines will likely depend on the existence or probable existence of high-reliability engines. In all likelihood, the expenditures necessary to make such improvements possible will require investment from both medical and nonmedical users of UAS technologies.

Regulatory requirements will influence the complexity and cost of these systems, as well as the speed and certainty of adoption. Costs will also have to

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85. Northwest UAV website, "NWUAV Commercial UAV Engines: NW-44, NW-88 & NW-500," accessed October 31, 2019, https://www.nwuav.com/engines-nwuav.html.
86. US Air Force website, "MQ-1B Predator," September 23, 2015, https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104469/mq-1b-predator/.
87. "Flight Test: Sonaca 200 Trainer Pro," *Pilot*, September 11, 2019.

scale upward as UAS capabilities and complexity increase. Cost matters—it is an important consideration when assessing the humanitarian applications that make sense for drones.

Necessary Advances in Vehicle Design

Multifunctionality of UAVs presents a serious design challenge. In addition to medical uses—the topic of this paper—UAVs are used for military reconnaissance, for search-and-rescue missions, for homeland security, and for other purposes. They must operate under a variety of conditions.

The menace for the engineers is a tendency to aim for a one-size-fits-all design. In other words, a team of designers has a menu of design objectives, and the designers effectively assign all of them equal priority. This tendency to design a UAV as one would a Swiss Army knife has been an error commonly made by design teams.

One of the authors of this paper (John Coglianese) has personal experience with projects in which large investments were made in a sophisticated design for a UAS intended to simultaneously achieve multiple challenging technical goals. The drive for multifunctionality led to an underemphasis on the selection of the drone's engine. Ultimately, designers overlooked the most fundamental requirement of all—simply achieving reliable flight. As we argue in this paper, a reliable, useful system of medical drones will require more powerful and reliable miniaturized engines than any that currently exist. Failure to recognize this paramount need will ensure failure of the technology.

Designing a UAS, like designing any complicated system, is challenging. Multiple goals—endurance, range, ease of launch and recovery, and payload capacity—compete with one another in a classic economic problem of multiproduct optimization under a budget constraint. The challenges of competing requirements in UAV design are well captured in a book by Reg Austin.[88] Austin spent his career in aeronautics and was a pioneer in the development of unmanned systems. His ideas on design stretch back as far as 1967. In the preface to *Unmanned Aircraft Systems*, Austin observes that "unfortunately, the vision of engineers and scientists is seldom matched by that of administrators, regulators or financiers." To put this another way, UAV design entails both engineering and internal politics.

88. Reg Austin, *Unmanned Aircraft Systems: UAVS Design, Development and Deployment*, Aerospace Series 55 (West Sussex, UK: Wiley, 2011).

To better illustrate this concept, let's consider the following example. Suppose there is a need for drone that meets the following specifications:

- It must be able to carry at least 50 pounds of medical supplies.
- It must be able to reach target locations in remote areas up to 200 miles from its home base.
- It must be able to reach target locations at altitudes higher than, say, 7,000 feet above sea level.
- It must be able to fly during times of the year when winds can gust over 40 miles per hour.
- It must be able to fly in a desert, where temperatures can exceed 110 degrees Fahrenheit during the summer.
- It must be able to fly in higher altitudes, where temperatures are below freezing in the winter.
- It must be able to be launched and recovered from locations that lack large open areas or runways—say, hospitals or firehouses.

The conditions described in these specifications easily apply to broad areas of the western United States.

In such circumstances, range, weight, and payload requirements are going to demand larger, gas-powered drones. While a limited number of low-horsepower internal combustion engines do exist today, each is optimal only over specific, discrete weight ranges. For some weight ranges, no optimal engine currently exists. Therefore, over those "missing" weight ranges, users will likely be forced to rely on larger, heavier, more expensive engines than are technically necessary, to ensure that the power plant is reliable.[89]

A fixed-wing aircraft, as compared with a multi-rotor drone, would be better suited to accomplish the range and payload requirements listed above. But a fixed-wing design is problematic owing to the launch and recovery constraints. These constraints demand a launch and recovery method that does not require a runway. One such method would be craft with vertical takeoff and landing (VTOL) capabilities; another would be the use of a specialized launch and recovery system. For instance, a launcher might utilize a bungee cord or pneumatics and a rail system to launch the aircraft. A net-capture system could be used to recover the UAV after a mission. Zipline's humanitarian missions in Rwanda provide a good example. The company uses a rail to launch its UAVs, and it recaptures the vehicles using a wire

89. *Power plant* refers to the entire propulsion mechanism—for example, an engine and propeller.

that the vehicle grabs with a mechanism on its belly. Zipline conducts long-range flights utilizing BVLOS. The rural nature of Rwanda and its looser regulation (as compared with the United States) make this configuration a more viable option.[90]

Now we have to consider the altitude from which the craft may have to operate. Many of the systems using VTOL capabilities or a launcher for takeoff would not be able to launch with 50 pounds of payload in the warmer months at higher altitudes. The air would be too thin for the vehicle to reach adequate aerodynamic lift. A rolling takeoff with a fixed-wing UAV provides the ability to take off at higher altitudes, but this requires a runway to conduct rolling takeoffs and landings. Higher altitudes will demand longer runways for longer rolling takeoffs.[91]

As we evaluate which type of aircraft best suits our needs, we can't ignore the transportation requirements. How mobile must this system be? Will it be able to be moved as needed using a single SUV, or must operators rely on a large tractor trailer? An unwieldy system may require several days for breakdown and setup, along with the expense of large crews.[92] The answers to these questions will significantly impact a UAS's design and cost.

Thus far, we have not even discussed the payload—the reason for the entire project. In order to protect the contents of the payload, the drone may require a payload bay that maintains a controlled temperature and environment. For example, Johns Hopkins researchers transported blood via drone over the Arizona desert in a temperature-controlled chamber.[93] Environmental-control provisions and payload-protection equipment will increase weight and power requirements.

How then do we solve, or at least mitigate, the problem of conflicting goals? One approach is to develop multiple drones—to have different arrows in the quiver, so to speak. For instance, on a day with moderate temperatures and no wind, operators might employ a VTOL solution from an outpost that can be more responsive and that launches its vehicles from a small parking lot. On a day with extreme temperatures and high winds, operators might have to employ a hardier system whose home base is farther away from the target location and less responsive, but which uses a small runway for a rolling takeoff and landing. The

90. Baker, "American Drones Saving Lives."
91. Aircraft Owners and Pilots Association website, "Density Altitude," accessed November 1, 2019, https://www.aopa.org/training-and-safety/active-pilots/safety-and-technique/weather/density-altitude#WIDA.
92. Austin, *Unmanned Aircraft Systems*.
93. Chanapa Tantibanchachai, "Drone Carrying Blood Samples Travels 160 Miles in Arizona Desert to Set New Record," Johns Hopkins University, September 19, 2017.

other approach is to prioritize the most important capability requirements and to make compromises. Is increased endurance worth reducing payload weight from 50 pounds to 25 pounds? Or would a 50-pound payload capacity justify a shorter range?

In the end, we have to accept that there are no silver-bullet solutions with drones. We may not always be able to come up with a design that meets all the conflicting needs. The challenge is to implement a design process that channels the competing goals and interests into an acceptable compromise, topped off by due diligence.

Communications and Security

A reliable and secure communications architecture is an essential ingredient for safe drone operations. The architecture, or network, encompasses several elements, including the transreceivers on the drone and on the ground, any other communications nodes such as cellular towers or satellite, and network nodes such as internet switches and Wi-Fi access points. In short, one must analyze the entire communications path that the command-and-control data will flow through to properly evaluate its reliability.

Some may argue that, because of the accuracy of GPS, there is no need to have a human in communication with the drone.[94] However, GPS will not suffice to ensure an adequate level of safety. The reasons are intuitive to those who use GPS for ordinary traffic guidance. At times, for example, a driver finds that a cell phone navigation app shows the vehicle driving on a road adjacent to its actual route. At times, GPS-driven apps place users hundreds of feet (or even yards) from their actual locations. The same technical problems could cause a GPS-reliant drone to fly into a building.[95]

Sense-and-avoid capability can mitigate such problems, but that technology is not yet sufficiently mature. Increasing its reliability will be costly, and as with any technology, it will not be foolproof. For this reason, having a human in the communications loop is essential to safe and reliable UAV operation. The communication connection must be constant and reliable to ensure that the operator has positive control of the drone. This does not mean that the pilot is, as

94. Fintan Corrigan, "Drone Waypoint GPS Navigation Technology and Uses Explained," *DronZon*, March 24, 2019.
95. "Strange GPS in Hong Kong—China Government Responsible?," Resilient Navigation and Timing Foundation, September 4, 2019.

a rule, controlling the course of the aircraft. It means that the pilot is on standby to take control of the flight if a problem arises.

Ensuring constant communication is not always a simple task. We can examine several different communications architectures to illustrate the point. First, consider a simple, straightforward architecture—a drone pilot with a controlling mechanism, communicating directly with a drone a few hundred yards away. The ability to measure risk here is not so complicated, but things become considerably more complex when the drone is a significant distance from the operator, as in BVLOS operation. In that case, several nodes must all perform simultaneously and reliably to ensure constant communication with no measurable delays in communication (latency).[96]

Here again, technology familiar to laypeople can suggest the challenges inherent in developing such a capability. We make cell phone calls to locations all over the globe. When we do so, we often experience dropped calls, sound quality "breaking up," echoes, delays in reception, and other issues. For telephone calls, such problems generally result in an annoyance. With UAVs, the equivalent problems could be lethal.

Communication interruptions can be caused by a variety of events occurring anywhere in that path between the transmitter and the receiver. Safe, reliable UAVs will need "lost link procedures": if the drone loses communication with its operator, it automatically executes specific procedures to minimize the likelihood of disaster scenarios. For example, lost link procedures might order an out-of-contact UAV to climb to a specific altitude, fly to a specific GPS coordinate, and then fly a predetermined orbit until communications are reestablished. An alternative lost link procedure might simply land the vehicle. This is a viable approach for drones flying in sparsely populated areas. However, in a densely packed urban environment, the challenges are much more significant. There is no way to predict when the loss of link might occur, and there are many obstacles (buildings, power lines, etc.) that would significantly increase the chances of an accident.[97] Vehicles delivering packages are likely to be flying near or around buildings. For safety reasons, there is little room for communications interruptions.

Reliability of communications is not the only consideration. Having a secure link is also of paramount importance to protect the link from being interrupted, jammed, or—in the worst-case scenario—taken over by an unauthorized

96. Yong Zeng, Qingqing Wu, and Rui Zhang, "Accessing from the Sky: A Tutorial on UAV Communications for 5G and Beyond," *IEEE*, March 14, 2019.
97. "ANSP Considerations for Unmanned Aircraft Systems (UAS) Operations," Air Navigation Service Provider, November 1, 2019.

agent. This challenge is not limited to UAVs. For example, a parallel effort is underway with respect to autonomous automobiles.[98]

It is nearly impossible to devise a foolproof communication node, but measures can be taken to mitigate the risk. The industry is actively devising counter-UAS systems to target hostile UAVs. Toward this end, many vendors are following familiar computer industry procedures to test vulnerabilities—replicating the communications protocol and hijacking the communications link, for example. Some vendors can command some drones to fly to their home bases or to land abruptly, and, in selected instances, they can completely take control of a drone.[99]

The fact that this hijacking capability exists today indicates that reliable safeguards must be in place to prevent such occurrences in civilian airspace. Protecting the data exchanged during communication is also important. (This includes both metadata, such as coordinates, and content, such as video.) Wireless transmissions from personal devices employ encryption. We use passwords to sign on to a website or device. We use authentication tokens. Unfortunately, drone operations often fail to employ these same familiar technologies. Before drones reach large-scale use in the United States, such protective technologies will be essential considerations for UAV operators and regulators alike. There is no such thing as a completely secure network, but using the tools available today can harden our communications architecture.

PUBLIC POLICY CHALLENGES

Enabling rapid growth in the use of UAVs, including those destined for medical uses, will require a multifaceted effort involving numerous federal, state, and local authorities. The FAA and its parent agency, the Department of Transportation, will have to define quality standards and, in essence, reconfigure the nation's half-century-old airspace architecture.[100] Given the critical nature of ground-to-UAV communications to safe and reliable operations, the Federal Communications Commission will have to establish parameters for those communications. Given the deliberate physical threats that drones can pose, there will be issues for the Department of Homeland Security to resolve (and potentially the Departments

98. Andy Lacher et al., "Unmanned Aircraft System Loss of Link Procedure Evaluation Methodology," *MITRE*, May 11, 2011; "Tesla Model S and Model 3 Vulnerable to GNSS Spoofing Attacks," *GPS World*, June 28, 2019.
99. Dan Goure, "Electronic Warfare Is Becoming the Most Lethal Counter Drone Technology," *Real Clear Defense*, September 20, 2019.
100. Brent Skorup, "Auctioning Airspace" (Mercatus Working Paper, Mercatus Center at George Mason University, Arlington, VA, November 2018).

of Defense and State, as well). Given the medical nature of the cargoes under discussion, the Department of Health and Human Services, the Food and Drug Administration, and the National Institutes of Health will also have interests. And finally, state and local lawmakers and regulators will have key roles in establishing UAV capability. The challenge for all will be to craft laws and regulations that yield a high degree of safety and reliability, but without suffocating the technology before it can fly.

Federal Aviation Administration

The FAA faces significant challenges to integrating drones into the National Airspace System within a short period of time, given the exponential growth of the drone industry.

In 2013, when Amazon announced its UAS delivery service, Prime Air, the FAA had not developed any regulations for UAV flight.[101] Amazon and other companies interested in utilizing this technology had to develop their drone business models internationally. Since 2013, the FAA has tried to move quickly (although industry would say not quickly enough) to develop a reasonable regulatory and safety apparatus for innovative delivery strategies such as those projected in urban air mobility.[102] (NASA defines urban air mobility as "safe and efficient air traffic operations in a metropolitan area for manned aircraft and unmanned aircraft systems.") Pressure on the FAA is increasing, as requests for special use permits by first responders and other parties multiply.[103]

A foundational regulatory step was the FAA's Small UAS Rule (Part 107), which provided basic operating rules for flying a drone commercially. This regulation established strict flight limitations, such as prohibitions against flying a drone beyond the visual line of sight, against flying over people or near airports, against operating a drone from a moving vehicle, and against flying above 400 feet during the day.[104] Additionally, it required commercial drone pilots to pass a remote pilot knowledge test before they could pilot a drone, demonstrating that

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101. Connie Lin et al., "Drone Delivery of Medications: Review of the Landscape and Legal Considerations," *American Journal of Health-System Pharmacy* 75, no. 3 (February 2018): 153.
102. "NASA Urban Air Mobility Market Study," NASA, November 1, 2018, https://www.nasa.gov/sites/default/files/atoms/files/uam-market-study-executive-summary-v2.pdf.
103. Vicki Speed, "FAA Requests for Emergency UAS Airspace Authorizations on the Rise," *Inside Unmanned Systems*, August 27, 2019.
104. Federal Aviation Administration, "FAA Fact Sheet—Small Unmanned Aircraft Regulations, Part 107," June 21, 2016.

they had achieved a basic understanding of airspace, safety, and the impact of weather on flight.

With the passage of the 2018 FAA Reauthorization Act, Congress moved to make the FAA accountable for generating a comprehensive plan for integrating UASs into the National Airspace System in a timely fashion.[105] As part of this drive to rationalize drone policy, Section 336—the Special Rule for Model Aircraft—was repealed; this means hobbyist drone pilots will now be required to take a knowledge-based pilot test before flying.[106] They will be subject to regulations similar to those that apply to commercial drone pilots. Another major impact of the act is a strengthening of counter-drone security at the policy level. Counter-drone technology refers to systems designed to detect and intercept rogue unmanned aircraft. According to Section 376 of the act, the FAA must develop a plan for full operational UAS traffic management and implementation of remote ID—a unique identifier for each machine, thus enabling authorities to identify who is legally responsible for a particular drone.[107]

However, in the midst of regulatory and policy development, the basic challenges of inserting cutting-edge technology into an antiquated National Airspace System must be acknowledged. The US national airspace was structured in the 1950s, when air traffic management separated aerial vehicles into differently defined airspaces. For example, Class B airspace extends vertically from the ground's surface to 10,000 feet above mean sea level, and the classification serves to protect the nation's busiest airports by restricting access to Class B airspace to specially trained pilots cleared by air traffic control. Classes A through E are controlled airspace and are actively managed by air traffic control.

Controlled airspace was initially constructed in order to avoid manned aircraft incursions and collisions in the era of radio and flight by sight. Before satellites and GPS, aviators avoided accidents with other aircraft solely by knowing the rules of the airspace they occupied, communicating frequently via radio, and scanning the horizon in a methodical fashion. These rules are still in active use today. Current technologies for navigation and collision avoidance are much more sophisticated than radio communication and human vision. Of course, when some portion of the communications network fails, radio and eyesight are still critical.

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105. James Poss, "The 'Why's' of the 2018 FAA Reauthorization Act," *Inside Unmanned Systems*, January 7, 2019.
106. Zacc Dukowitz, "New FAA Reauthorization Act Has Big Implications for Hobbyist Drone Pilots," *UAV Coach*, October 10, 2018.
107. Isabella Lee, "White House Approves FAA Reauthorization Act and Moves Forward on UAS Traffic Management and Remote ID," *UAV Coach*, September 27, 2018.

The current National Airspace System infrastructure cannot support the transportation technology that exists today, since the system enforces a set of antiquated rules designed for sight- and radio-based navigation. The goal should not be regulating various airspace types, but rather separating aircraft (manned and unmanned) from other aircraft regardless of airspace. Controlled airspace in essence requires aircraft to fly under the constant instruction of air traffic control. This is inefficient, given the automated ability of aircraft to detect and avoid other aircraft without contemporaneous human input. The status quo in US aviation is analogous to having a ground traffic controller telling you where to drive your car and which highway to take each morning as you head to work. This would be an extremely inefficient way to manage commuting, both for commuters and for controllers.

No doubt, restricted areas will be a part of any system of airspace allocation for UAVs. To put things into perspective, the space shuttle *Columbia* was destroyed by a glancing blow from a 1.7-pound chunk of foam traveling at perhaps 550 miles per hour relative to the shuttle. In contrast, a direct hit from an 80-pound drone, traveling at 60 miles per hour relative to a missile in flight, would likely do even more damage than the *Columbia* foam strike. Hence, there is good reason to avoid having UAVs flying willy-nilly about Cape Canaveral, Vandenberg Air Force Base, Wallops Island, or other missile launch sites. In fact, NASA has had a bird abatement program at Cape Canaveral since a shuttle in flight experienced a potentially catastrophic strike by a turkey vulture in 2005. (Turkey vultures typically weigh only 3 to 5 pounds—a small fraction of a drone's weight.)[108]

Large-scale use of UAVs for medical and other purposes must carry forward the laudable culture of air safety in the United States while taking the best of emerging technologies and integrating them into aviation. Unfortunately, 70 years of regulations designed around earlier modes of manned flight are apt to serve more as a barrier than as an aid to this end. But efforts are underway to develop an unmanned traffic management system, parallel with and integrated into the present-day air traffic control system.[109]

One of the key players in developing a workable air traffic management system is NASA's Ames Research Center.[110] Ames is collaborating with the FAA to develop a platform that will enable each user to digitally share flight plans, enabling equivalent situational awareness of airspace with the ultimate goal of

108. "Bye Bye, Birdies," NASA, June 30, 2006.
109. "A Deep Dive into UTM and the Flight Information Management System for Drones [Long Form]," *Dronelife*, August 22, 2019.
110. "What Is Unmanned Aircraft Systems Traffic Management?," NASA, May 3, 2019.

safely integrating drones into urban areas. A key research component is situational awareness through detect-and-avoid technology. Before the FAA can establish unmanned traffic management regulations, a series of experiments must be performed in order to establish technical requirements and pilot protocols for safe flight. Equally important is the successful enforcement of unmanned traffic management regulations once they are developed. A means of identifying both drone and pilot is critical and has yet to be developed.[111]

Finally, one obstacle slowing the diffusion of UAV technology is lags in the approval process at the FAA. Toward the goal of removing this obstacle, US Reps. Mark Meadows (R-NC), Henry Cuellar (D-TX), and David Rouzer (R-NC) introduced H.R. 2830—the Drone Backlog Reduction Act. This bill directs the FAA administrator to "create a task force to process applications submitted for determinations, assessments, and waivers for unmanned aircraft systems."[112]

Federal Communications Commission

Dedicated bandwidth is critical for reliable UAS command-and-control communication. Otherwise, without reliable pilot-in-command communication with the UAV, BVLOS flight becomes untenable. For this reason, the 2018 FAA Reauthorization Act instructs the FAA, the National Telecommunications and Information Administration, and the Federal Communications Commission to study and report on whether drones can operate on specific band frequencies within the C and L ranges of the broadcast spectrum (4 to 8 GHz and 1 to 2 GHz, respectively). If those two ranges are inadequate for the task, the agencies must recommend other frequencies.[113]

Use of satellite communications will be critical for UAV flight beyond the visual line of sight. Typical mobile air-to-ground links (e.g., cell towers) are limited by range, and coverage is often sparse in areas with low population densities—the very areas that are most attractive for drone use. For now, the costs of using satellite communication networks for data streaming can be prohibitive.

Unfortunately, the use of C and L band frequencies is already competitive, with the mobile telecommunications industry using most of the spectrum allotted to civilian use. Expanding civilian-use spectrum and dedicating bandwidth to UASs will be essential for the positive growth of the drone industry. The satellite network needs to be expanded to make satellite communications cost

111. Michael Behar, "Drones in a Busy Sky," *Air & Space Magazine*, August 1, 2016.
112. Drone Backlog Reduction Act of 2019, H.R. 2830, 116th Cong. (2019).
113. Poss, "'Why's' of the 2018 FAA Reauthorization Act."

effective. In response to the demand for reliable long-distance communication, companies such as Hughes Network Systems are working on expanding satellite communication systems by developing LEO (low Earth orbit) systems and other technologies to amplify satellite capacity.[114]

Technology companies and the Federal Communications Commission are currently grappling with the regulatory framework necessary to implement 5G (fifth-generation) wireless standards, which will allow faster, more powerful, more reliable wireless communication.[115] Brent Skorup of the Mercatus Center at George Mason University notes that regulatory action by both the commission and local authorities is essential to implementation.[116] It should also be noted that potential dominance of 5G technology by China has raised concerns in defense circles.[117]

Departments of Defense and Homeland Security

Drones are an important and growing capability for the Department of Defense. The maturity and capability of UAVs are light-years ahead of what existed 25 years ago. As a result of this incredible growth and development, innovators are aggressively pursuing everyday commercial and humanitarian applications of the technology—including medical applications. But these applications also bring significant risks that must be addressed by the Secret Service, the Department of Homeland Security, federal law enforcement agencies, and state and local authorities.

Drones can be dangerous to manned aviation. The challenge for agencies charged with public safety lies in finding a "Goldilocks" spot—rational regulation sufficient to stave off most disasters, but not so heavy as to smother the technology. Too little regulation might allow disasters—accidental collisions with manned airplanes, hostile military reconnaissance, terrorism. Aside from the immediate risks, there is the very real possibility that a single disaster could destroy public support for and government allowance of widespread UAV use. The *Hindenburg* disaster effectively ended widespread use of dirigibles. A 1977

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114. Rick Lober, "Innovative SATCOM Solutions for Evolving UAS Requirements" (presented at Unmanned Aircraft Systems West for Defense Government and Industry Symposium, San Diego, CA, February 7–8, 2019).
115. Hanif Ullah and Nithya Gopalakrish, "5G Communication: An Overview of Vehicle-to-Everything, Drones, and Healthcare Use-Cases," *IEEE*, January 1, 2019.
116. Brent Skorup, "5G Basics and Public Policy" (Policy Brief, Mercatus Center at George Mason University, Arlington, VA, February 2019).
117. Rebecca Kheel and Ellen Mitchell, "Pentagon Fears Losing Race for 5G to China," *The Hill*, September 25, 2018.

accident atop what was then the Pan Am building in New York City severely limited the use of commercial helicopter transport within the city.[118]

These concerns are as real as the potential of drone technology. In the late 2010s, the press has carried numerous stories on near misses with commercial aircraft and threats of drones shutting down airports. These incidents have raised serious concerns and have had measurable financial implications.[119]

The risk extends well beyond damage to or destruction of an airplane. The scenarios are endless of how this technology can be used in less-than-productive ways. Drones have been used to fly contraband into prisons.[120] Drones have transported illegal drugs over the US-Mexico border.[121] UAVs pose potential threats to officers of law enforcement agencies. Criminals can now afford airborne imagery surveillance at night while agents conduct raids. Drones modified to carry a small firearm or drop an explosive device are a real threat. Malefactors have the ability to engage first responders by flying a drone into their vicinity with the intent to harm or kill.[122] Agents from the Drug Enforcement Administration; the Bureau of Alcohol, Tobacco, Firearms and Explosives; Customs and Border Protection; and Immigration and Customs Enforcement are all at risk from surveillance or attack by UAVs. UAV-enabled attacks could result in diminished enforcement ability or physical harm.

Soon, commercially available products with viable industrial applications could be modified or simply misused to pose serious threats. A simple example might be a drone that carries a nail gun to assist a roofing company; such a device could easily be weaponized.[123]

Concerns go beyond physical threats to personnel. Purposefully or even accidentally, UAVs can threaten data security for government agencies and private industry.[124] In the 1977 film *Black Sunday*, a villain commandeers the Goodyear Blimp to menace the Orange Bowl Stadium in Miami during the Super Bowl. While that scenario was somewhat far-fetched, an explosives-laden drone offers

118. Alex Cooke, "What Would Actually Happen If a Drone Hit an Aircraft," *FStoppers*, October 6, 2018.
119. Simon Calder, "Gatwick Drone Disruption Cost over £50m," *Independent*, January 22, 2019.
120. Bart Jansen, "FAA Prohibits Drone Flights over Federal Prisons, Coast Guard Bases," *USA Today*, June 26, 2018.
121. Mark Osborne, "Border Patrol Seizes Aircraft Loaded with Meth, Fentanyl after It Flies into US," *ABC News*, May 25, 2019.
122. Cyrus Farivar, "Man Who Built Gun Drone, Flamethrower Drone Argues FAA Can't Regulate Him," *Ars Technica*, June 9, 2016.
123. Devin Coldewey, "Take Cover! It's a Drone with a Nail Gun," *TechCrunch*, September 20, 2019.
124. David Shortell, "DHS Warns of 'Strong Concerns' That Chinese-Made Drones Are Stealing Data," *CNN*, May 20, 2019.

a more practical tool for causing similar terror at sports events, concerts, or political rallies. Unlike the Goodyear Blimp, the tools necessary for UAV-borne terrorism are quite affordable.

While drones controlled by medical providers would likely be less prone to such malicious uses than would drones used for other purposes, they would exist within the broader UAV universe. Public panic over UAVs in general could limit the capacity to deploy lifesaving drones for medical uses. The potential dangers are impossible to ignore and should not be disregarded for the sake of technological advancement. Federal agencies are already preparing for a world in which the number of UAVs aloft burgeons and their purposes multiply. Drones, of course, are also tools of the very agencies (e.g., the Drug Enforcement Administration and the Bureau of Alcohol, Tobacco, Firearms and Explosives) that can be the targets of malicious operators. The big task ahead for such agencies is understanding how to mitigate threats without sacrificing the technology itself.[125]

Already, these agencies are working with the FAA and other regulators to define rules that allow for constructive uses of drones while simultaneously layering in prudent measures that provide adequate security and safety to infrastructure and people.[126] The Department of Transportation, for example, recently sent a proposal for remote identification of drones to the White House for consideration.[127]

In fall 2019, a bipartisan group of senators introduced the American Security Drone Act, which would prohibit federal agencies from purchasing off-the-shelf UAVs from China or other countries deemed to be security risks. As part of a review process, the Department of the Interior decided in late 2019 to cease using Chinese-made drones for nonemergency uses.[128] No specific reason was given for the decision.[129]

Also in fall 2019, Senator Mike Lee (R-UT) introduced the Drone Integration and Zoning Act, which would grant individual property owners discretion over drone traffic flying over their land at 200 feet or lower.[130] This approach—

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125. US Department of Homeland Security, "Unmanned Aerial Systems," accessed October 16, 2019, https://www.dhs.gov/science-and-technology/unmanned-aerial-systems.
126. Steve Amitay, "New Aviation Law Makes Positive Changes to Current Rules for Commercial Drone Use," ASIS International, November 1, 2018.
127. "Proposed UAS Remote Identification Rule at White House for Review," Hogan Lovells, September 19, 2019.
128. Melina Druga, "Interior Department Grounds Drones Made in China," *Federal Times*, November 6, 2019.
129. Katy Stech Ferek, "Lawmakers Seek Ban on Chinese Drone Purchases by Federal Agencies," *Wall Street Journal*, September 18, 2019.
130. Noah Shepardson, "Sen. Mike Lee Would Let You Decide If Drones Can Fly Less Than 200 Feet above Your House," *Reason*, October 17, 2019.

modeling far-reaching decentralization—contrasts with other commentators' and policymakers' desire to centralize control over all airspace within the FAA.

Medical Agencies

The federal agencies focused on health—particularly the Department of Health and Human Services, the Food and Drug Administration, and the National Institutes of Health—also have direct interests in the deployment of medical drones. A 2018 article surveyed the literature on potential medical applications of UAVs.[131] The study examined papers dealing with the deployment of drones to transport blood samples and defibrillators, search for lost or injured individuals, and transport surgical gear in battlefield settings. All nine of the papers examined found that drones improved performance. This survey was funded by the US National Heart, Lung, and Blood Institute, which is part of the National Institutes of Health.

Also in 2018, the federal government's Small Business Innovation Research seed fund program solicited applicants to "develop a prototype capability that will leverage emerging UAS technologies to provide secure emergency 'just-in-time' delivery and recovery of whole blood products via Unmanned Aerial Systems (UAS) to and from medical personnel at remote and austere locations in support of Prolonged Field Care."[132] And the Food and Drug Administration has been examining how drones could be used in conducting health inspections of agricultural facilities.[133]

A 2018 paper outlined regulatory considerations concerning medical device drones (MDDs):

> Because MDDs will often carry biologics such as blood or tissue samples, they will be thoroughly regulated by the litany of agencies currently governing medical courier companies, including: (1) the International Civil Aviation [Organization] [ICAO]; (2) International Air Transport Association (IATA); (3) [Department of Transportation], [Centers for Disease Control and Prevention] (CDC); (4) Transportation Security Administration (TSA);

131. R. M. Carrillo-Larco et al., "The Use of Unmanned Aerial Vehicles for Health Purposes: A Systematic Review of Experimental Studies," *Global Health, Epidemiology and Genomics* 3 (2018).
132. "Emergency 'Just-in-Time' Delivery and Recovery of Whole Blood via Unmanned Aerial Systems," Small Business Innovation Research, April 20, 2018.
133. Mohana Ravindranath, "FDA Is Looking into Drones for Health Inspections," *Nextgov*, July 26, 2017.

(5) Food and Drug Administration (FDA); (6) Occupational Safety and Health Administration (OSHA); and (7) the FAA.[134]

The 21st Century Cures Act created "Eureka Prizes"—retrospective monetary awards for innovators who accomplish specific, well-defined technological goals.[135] This funding method contrasts with more common prospective grants—in which federal agencies fund specific researchers in hopes that the money will spur innovation.[136] The logic behind the prizes is that it may be impossible to determine in advance which innovator will solve a particular technical challenge (for example, creating improved sense-and-avoid technology). Retrospective prizes, which hark back to the United Kingdom's Longitude Act of 1714, may be an appropriate pathway toward completing some of the daunting tasks that innovators and policymakers face with respect to drones.

States and Localities

States and localities, too, have their role in opening the skies to medical and other drones. In 2019, for example, the New Hampshire legislature considered a bill that would authorize the state's secretary of transportation to regulate drones.[137]

Under the leadership of the US Department of Transportation and the FAA, the UAS Integration Pilot Program (IPP) is currently being conducted at the state and local government level. The program's goal is to identify ways to balance national and local interests in the development of new regulations for the use of UASs in very low-level (VLL) airspace.[138]

Ten state, local, and tribal government entities were selected to participate in the IPP and then to partner with the private sector. These included the Choctaw Nation of Oklahoma; the City of San Diego; Virginia Tech Center for Innovative Technology; the Kansas Department of Transportation; Lee County Mosquito Control District (in Florida); Memphis–Shelby County Airport Authority (in Tennessee); the North Carolina Department of Transportation; the North Dakota Department of Transportation; the City of Reno, Nevada;

134. Luke Striber, "Safety Meets Efficiency: The Medical Device Drone's Role in Bringing About a Workable Regulatory Framework for Commercial Drones," *Journal of Air Law and Commerce*, January 1, 2018.
135. 21st Century Cures Act § 2002, Pub. L. No. 114-255 (December 13, 2016).
136. Robert Graboyes, "How Eureka Prizes Will Create a New Age of Discovery," *Washington Examiner*, December 5, 2016.
137. Bob Sanders, "On the New Hampshire Legislature's Agenda This Week," *New Hampshire Business Review*, January 19, 2019.
138. "UAS Integration Pilot Program," Federal Aviation Administration, October 16, 2019.

and the University of Alaska Fairbanks.[139] Over approximately three years, the participants will gather UAS data on night operations, BVLOS flight, flight over people, detect-and-avoid technologies, package delivery, and the reliability of command-and-control systems.

About half of the IPP participants are looking at the use of UASs in healthcare. The University of San Diego is seeking to establish an autonomous drone delivery network for the transportation of patient blood and pathology specimens.[140] The North Carolina IPP participant's main goal is to partner with global drone delivery companies Zipline, Matternet, and Flytrex to establish a network of medical distribution centers that can use drones to make medical deliveries.[141] North Dakota plans to use UAVs for emergency response during life-threatening events in rural areas, such as for search and rescue in the Badlands.[142] The City of Reno, Nevada, has partnered with Flirtey to test the use of drones for AED delivery to cardiac arrest patients in Washoe County, Carson City, and the Reno-Sparks Indian Colony.[143] And Alaska included transport of medical supplies to remote areas and search and rescue as possible projects among its other goals.[144]

Successful implementation of drones for a variety of purposes may depend on whether governments will adopt a unique set of rules for VLL airspace rather than using those currently applied to the national airspace. With state and local collaboration, the FAA could craft such rules. An important question is whether the FAA would administer such rules directly or whether VLL airspace would be under municipal control, with the FAA as a supervisory agency. A national strategy will be needed to coordinate interstate transportation, at least, and to provide for legislative templates flexible to technological change and innovation. However, input from local communities is essential to managing the upsurge in VLL airspace activity.

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139. Elaine L. Chao, "Unmanned Aircraft Systems Integration Pilot Program Selectees," Department of Transportation, May 15, 2019.
140. "Meet the IPP Sites: City of San Diego Pursues Several Diverse UAS Applications," *AUVSI News* (Association for Unmanned Vehicle Systems International), October 23, 2018.
141. Brian Sprowl, "Meet the IPP Sites: North Carolina Department of Transportation and Partners Using UAS to Deliver Medical Supplies in North Carolina," *AUVSI News* (Association for Unmanned Vehicle Systems International), November 26, 2018.
142. "NDDOT Receives Federal Waiver to Fly Drones over People," North Dakota Department of Transportation, June 25, 2019.
143. "City of Reno UAS Integration Pilot Program," City of Reno Government, May 1, 2018.
144. Sue Mitchell, "UAF Selected for New Federal Drone Program," University of Alaska Fairbanks, May 8, 2018.

INDUSTRY AND POLICY CHECKLIST

We can extract from the above text a checklist of to-do items for the drone industry and for policymakers. These are actions that would be helpful or essential to timely, large-scale, nationwide deployment of medical and nonmedical UAVs. On the industry side, possible tasks ahead include the following:

- Develop more reliable ground-to-air communication systems.
- Deploy a sufficient satellite network to accommodate UAS communications and tracking.
- Develop reliable lost link procedures.
- Develop highly reliable sense-and-avoid technology with machine learning capabilities.
- Harden UASs against interference by hackers and terrorists.
- Determine technological developments essential to BVLOS flight.
- Develop reliable lightweight internal combustion engines for long-distance flights.
- Design and manufacture different drones for different purposes.
- Increase payload and capacity range beyond the capabilities of today's UAVs.
- Harness Eureka Prize funding for medical drone advancements.

On the policy side, possible tasks ahead include the following:

- Expedite the approval of novel medical UAS missions, including BVLOS operations.
- Establish a framework for coordinating various federal, state, and local agencies to minimize bottlenecks.
- Determine the boundaries of federal, state, and local authority over UAV airspace.
- Establish the legal rights of property owners concerning drone traffic in the air above their land.
- Reconfigure the national airspace architecture to accommodate large-scale UAS deployment.
- Develop an unmanned traffic management system parallel to today's air traffic control system.

- Determine the placement and enforcement of no-go zones, such as sensitive military facilities and missile launch sites.
- Dedicate sufficient bandwidth to accommodate UAS communications.
- Clarify rules about the use of drones manufactured in China and elsewhere.

Perhaps the greatest challenge in all of this is the presence of chicken-and-egg problems. The drone industry will have to spend enormous sums to develop the vehicles and communications necessary for a viable system of medical drones, but innovators and investors are unlikely to expend their resources without guarantees that their vehicles will be deployable at the end of the day. But policymakers will likely hesitate to grant such guarantees without a high degree of certainty that the as-yet-to-be-developed vehicles will attain desired levels of safety. The task ahead is to devise a legal and regulatory framework—in essence a contract between industry and government—to overcome this problem.

This leads to one final and perhaps critical element of the process: Industry and policymakers will likely have to agree, sooner rather than later, to a clear framework for establishing liability for accidents and ensuring that there will be sufficient capital to finance tort judgments and settlements when needed. This requires the refinement of the US system of indemnification and the rules governing that system—insurance, in other words.

CONCLUSION

The United States is in a period of great foment regarding the potential of UAVs for both medical and nonmedical applications. This paper has explored a range of topics important to the advancement of medical UASs. Medical drones are already performing valuable, lifesaving functions in several developing countries. These cases demonstrate the potential value of similar uses in developed countries. However, large-scale drone use is far more problematic in countries like the United States because their airspaces are already heavily used. Nevertheless, drones are still likely to play important roles in developed countries—especially in remote areas, during harsh weather conditions, and in places where traffic congestion is a problem. While proponents speak of efficiency and cost savings, the most compelling argument for medical drone use in America is humanitarian—the ability to save lives and relieve suffering when time is especially critical.

The greatest challenge will come in attaining safe, commonplace use of BVLOS capability. This will require advances in engines and airframes, in overcoming communications challenges, and in developing extreme reliability on the part of the overall systems. Achieving these goals will also require a high level of coordination among multiple federal agencies, along with state and local authorities.

AFTERWORD: A RELEVANT NOTE ON THE AUTHORS

To give this paper a bit of context, it will be helpful for readers to understand the internal discussions that have gone into its writing. The three authors come from vastly different backgrounds, and their internal discussions are a microcosm of discussions in the larger policy sphere. Consider how their backgrounds influenced their discussions of cost considerations.

Robert F. Graboyes is an economist who focuses on the technology of healthcare, and he is a self-described techno-optimist. His writings have included a decidedly pro–medical drone article, titled "Will America Catch Up with East Africa in Adopting Medical Drones?" In that article, Graboyes argued that "East Africa now has the world's most advanced drone delivery system for medical supplies. The question for America is whether we will follow these countries' leads, thereby reducing costs and increasing efficiency of life-saving services in our own rural and remote areas."[145]

Darcy Nikol Bryan is an obstetrician and gynecologist whose patients are precisely the type who may need rapid life-saving interventions—the sort of patients Zipline claims its drones have saved in Africa. Bryan also flies small aircraft for pleasure and is a licensed drone operator. Together, Bryan and Graboyes wrote an article, "Drones Delivering Medical Supplies and More Can Help Save American Lives," in which they argued that "drones also have cost advantages. A 25-pound drone carries supplies less expensively than a 2-ton automobile or 3-ton helicopter. And there's no need to pay an employee to travel the distance with a car or helicopter."[146]

John Coglianese is a retired US Marine Corps officer who held a senior leadership position in the US military's UAV programs. Coglianese has impressed upon his coauthors caveats to the idea that drones will necessarily save money, compared with other modes of transport. Having worked on the design of UAVs and UASs—software, buildings, communications systems, personnel, etc.—he stresses the enormous expenses that will accompany the development of safe, reliable, powerful, versatile UAVs. While UAVs can cut costs in certain areas, for

145. Robert Graboyes, "Will America Catch Up with East Africa in Adopting Medical Drones?," *Real Clear Health*, August 25, 2017.
146. Robert Graboyes and Darcy Nikol Bryan, "Drones Delivering Medical Supplies and More Can Help Save American Lives," *STAT*, January 18, 2019.

quite some time cost-cutting is unlikely to be the most compelling argument for medical drones.

Rather, as discussed above, the most compelling argument in the near term is a humanitarian one. In certain situations, UAVs can cut delivery times, and those time savings can mean the difference between life and death for certain patients.

As Coglianese informed his coauthors, military technologists have a saying: "Crawl, walk, run." Deploy a new technology slowly, carefully, and selectively at first, then expand it, and finally extend its uses toward more challenging and more optional situations.

Coglianese has also impressed his optimistic coauthors with the obstacles that stand between today and the futurist vision of a world in which the skies are filled with drones. In 2017, the Federal Aviation Administration estimated that the number of hobbyist drones would grow from 1.1 million in 2016 to more than 3.5 million by 2021. The agency estimated that the number of commercial drones could grow from 42,000 in 2016 to as many as 1.6 million by 2021.[147] The authors of this paper suspect that growth will be considerably slower—that the challenges of designing better vehicles, achieving airspace reform, and making regulatory adjustments will limit medical and other commercial UAVs to niche services for quite some time.

However, if consideration of these challenges induces a bout of techno-pessimism, it is helpful to recall a quote from the *New York Times* in 1985:

> The real future of the laptop computer will remain in the specialized niche markets. Because no matter how inexpensive the machines become, and no matter how sophisticated their software, I still can't imagine the average user taking one along when going fishing.[148]

147. David Shepardson, "U.S. Commercial Drone Use to Expand Tenfold by 2021: Government Agency," *Reuters*, March 21, 2017.
148. Erik Sandberg-Diment, "The Executive Computer," *New York Times*, December 8, 1985.

ABOUT THE AUTHORS

Robert F. Graboyes is a senior research fellow at the Mercatus Center at George Mason University. Author of "Fortress and Frontier in American Health Care," he asks in his work, "How can we make healthcare as innovative in the next 30 years as information technology was in the past 30 years?" Previously, he was a senior healthcare adviser for the National Federation of Independent Business; sub-Saharan Africa economist for Chase Manhattan Bank; regional economist and director of education at the Federal Reserve Bank of Richmond; and a professor at five universities. He traveled extensively in Africa for Chase and was a visiting healthcare scholar in the Republic of Kazakhstan. He earned five degrees, including a PhD in economics from Columbia University. In 2014, Graboyes received the Reason Foundation's Bastiat Prize for Journalism.

Darcy Nikol Bryan, MD, is an associate clinical professor at the University of California Riverside and has an active practice in obstetrics and gynecology. She is a certified remote pilot and student private pilot. Her research encompasses public policy and the impact of technology on healthcare provision with a focus on women's health. She coauthored the book *Women Warriors: A History of Courage in the Battle against Cancer* (1st Book Library, 2002).

John Coglianese is a retired military intelligence officer who has significant experience in the field of unmanned aerial systems. His experiences have included the operational planning and employment of these systems as well as the development, testing, evaluation, and fielding of these systems for the Department of Defense.

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