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Surgical and Medical Applications of Drones: A Comprehensive Review

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ABSTRACT

Background: Drones have the ability to gather real time data cost effectively, to deliver payloads and have initiated the rapid evolution of many industrial, commercial, and recreational applications. Unfortunately, there has been a slower expansion in the field of medicine. This article provides a comprehensive review of current and future drone applications in medicine, in hopes of empowering and inspiring more aggressive investigation.

Database: A literature search was performed by EBSCO (Elton B. Stephens Company) Discovery Service, searching the phrases "drones," "UAV," "unmanned aerial vehicles," "UAS," and "unmanned aerial systems." A second search was used to identify sources that contained "drone" in the subject or title and "medicine" in any of the text, yielding 60,260 results. After screening for irrelevant material, 1296 sources remained applicable. Major themes and number of sources were as follows: 116 public health and medical surveillance, 8 telemedicine, and 78 medical transport systems.

Conclusion: Drones are used for surveillance of disaster sites and areas with biological hazards, as well as in epidemiology for research and tracking disease spread. Telecommunication drones are being used for diagnosis and treatment, perioperative evaluation, and telementoring in remote areas. Drones have the potential to be reliable medical delivery platforms for microbiological and laboratory samples, pharmaceuticals, vaccines, emergency medical equipment, and patient transport. Government agencies have placed drone use on the national agenda. The next steps include aggressive research initiatives in the areas of safety, industry expansion, increased public awareness, and participation.

Key Words: Disaster planning, Delivery of healthcare, Epidemiological monitoring, Telecommunications, Telemedicine.

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INTRODUCTION

The more familiar public term "drone" was first coined because of the similarity of the loud and cadenced sound of old military unmanned target aircraft to that of a male bee. Despite its public popularity, the term has encountered strong opposition from aviation professionals and government regulators. The term unmanned aerial vehicle (UAV) was first coined in the 1980s to describe autonomous, or remotely controlled, multiuse aerial vehicles that are driven by aerodynamic forces and are capable of carrying a payload.[1] This definition framed the distinction between UAVs from other aerial systems, such as ballistic vehicles, gliders, balloons, and cruise missiles. The more accepted term in professional circles, unmanned aerial systems (UAS), refers to one or more unmanned aerial vehicles in conjunction with a data terminal, with a sensory array and an electronic data link on the vehicle.[2] Other terms used to reference the drone include remotely piloted vehicle (RPV) and remotely piloted aircraft system (RPAS). RPV has been used mostly in military settings, whereas RPAS is the more formal and internationally accepted term.[3] For simplicity, throughout this article, the term drone will be used.

Drones typically consist of an air frame, propulsion system, and navigation system. They include a wide variety of aircraft design configurations and supporting tools that facilitate various applications. Although this technology is not new, it has only recently begun to meet conventional business applicability by providing a cheaper, faster, and better option than full-size aircraft. Through the development of microminiaturization and widespread production of underlying technology, including processors, microelectricalmechanical systems (MEMS) sensors, and batteries produced for smart devices, drone designs have become more capable, affordable, and accessible.[4]

There are several distinct drone designs; in addition, further categorization is based on regulatory requirements of sizing and performance. The common configurations include fixed-wing, rotary-wing, multirotor, and hybrid designs. These designs are typically modular and scalable in nature that feature reconfigurable payload and ground control options. Payloads can include remote sensing equipment, including electro-optical (E-O) with color, infrared, multispectral, and hyperspectral cameras. Others options are synthetic aperture radar (SAR), light detection and ranging radar (LiDAR), ground-penetrating radar, direct measurement sensors (gaseous, particulate matter, and meteorological), communications equipment (receipt, transmission, and relay), and cargo. Designs can also be categorized based on (*1*) operational profiles, such as horizontal take-off and landing (HTOL; ie, conventional airplane launch and recovery) and vertical take-off and landing (VTOL)[5]; (*2*) regulatory categories, that include small UAS (under 55 pounds) and UAS (55 pounds or greater)[6]; (*3*) governmental convention, such as the Department of Defense group schema (groups 1–5),[7] based on weight and performance; (*4*) propulsion design composition (electric or internal combustion); or (*5*) application-specific configuration, including intelligence, surveillance, and reconnaissance (ISR); cargo delivery and resupply; and communications relay.[8]

All civil UAS operations in the National Air Space (NAS) are conducted under Title 14 of the Code of Federal Regulations (CFR); with most complying as recreational users under 14CFR Part 101 or public/civil users under Part 107. Operation under part 101 requires compliance with a national community-based organization (CBO), such as the Academy of Model Aeronautics. Recreational UAS operation under a national CBO framework are only intended for personal enjoyment, hobby, or non–training-related educational pursuits and does not require licensure or certification. Operations under Part 107 require remote pilot certification, either through (*1*) successful completion of a specific knowledge test (Unmanned Aircraft General [UAG] Knowledge Examination) or (*2*) already holding a current manned flight rating (eg, Part 61; private, instrument, or commercial rating) and completing an online safety course. Such certification is necessary to ensure proper awareness of rules governing the safe application of this technology among other users of the NAS. In addition, a series of alternative options exist to gain access to the NAS for operations not in compliance with Parts 101 and 107; specifically, a Certificate of Waiver (COW) to Part 107, public Certificate of Authorization or waiver (COA), Section 333 Civil COA, and special airworthiness certificate (SAC; eg, experimental or restricted category). Application and approval of these alternative options require detailed analysis and proof of concept that the proposed noncompliance will still ensure an equivalent level of safety within the NAS and are reviewed and approved on a case-by-case basis by the Federal Aviation Administration (FAA).[9] Given the integration of drone technology into numerous commercial, research, and civilian applications, the growing drone industry is poised to make a significant impact on the global economy. A study by the Association for Unmanned Vehicles Systems International (AUVSI) postulates that once unmanned aerial systems have been incorporated into the NAS, the market will grow sustainably. It is projected to reach $82.1 billion by 2025. Furthermore, more than 103,000 jobs will be added in the same time frame. Current economical inhibitions primarily revolve around a lack of regulatory structure, airspace restrictions, and limitations of nonmilitary usage of drones.[10]

History

The development of drones is deeply rooted in military history. The U.S. Navy along with a team of British researchers at the Ordnance College of Woolwich first experimented with aerial torpedoes in an effort to combat German U-boats in World War One (WWI). These attempts fueled investigation into pilotless aircraft. From 1922 to 1925, the Navy tested radio control systems on the N-9 Aircraft. In 1924, the first successful radio-controlled flight was conducted from takeoff to landing.[11]

Drones had their initial use as targets for weapon accuracy practice in World War II. However, in 1942, the Navy developed a radio-controlled drone that carried a torpedo. These drones, designated TDR-1, were designed with television guidance systems and were controlled by a trailing aircraft.[12] At the same time, the U.S. Air Force (USAF), through a similar operation named the Aphrodite Project, transformed old Boeing bomber planes into unmanned aircraft equipped with radio control systems, television cameras, and 18,000 pounds of explosives.

During the Korean War, Hellcat fighter aircraft were converted to drones and loaded with 1000 pounds of explosives. They were then deployed in an attempt to destroy North Korean power plants and railway lines. In the 1950s, the U.S. Navy developed the first operational unmanned helicopter created in an effort to counter the threat of the Soviet submarine forces. The QH-50 helicopter was remotely controlled from a destroyer deck and carried torpedoes, sonar devices, or nuclear charges. Concomitantly, the Ryan Aeronautical Company created a jet-propelled, subsonic unmanned aircraft called the Firebee. Initially, they were used for target practice.[12] In the 1960s, the company modified these aircraft into reconnaissance drones called Lightning Bugs, with a range of 2500 miles.[13] The Vietnam War became the first war in which the United States extensively used drone technology, with 3435 UAV missions deployed between 1964 and 1975. These missions were flown by the Lightning Bugs, and were used primarily for reconnaissance and missile interception.[12] Drones received more widespread attention after their use during the Yom Kippur War in 1973. The Israeli Air Force deployed drones to provide crucial real-time images of enemy threats and targets. Increased cooperation between the United States and Israel led to the U.S. Navy's acquiring Israeli Pioneer drones, which were used very effectively during the Persian Gulf War. By the end of the 1990s, drones had become a crucial component of most prominent national militaries.[14]

In response to a request from the U.S. Department of Defense in 1996, the USAF developed the Predator drone, an unmanned remote-operated aircraft with reconnaissance, intelligence, and surveillance capabilities. After the September 11, 2001, attacks on the World Trade Center, the Predators were equipped with Hellfire missiles and were used to fight the War on Terror declared by the Bush administration. Thereafter, the U.S. military developed the MQ-9 Reaper, which can carry 8 Hellfire missile and flies twice as high and fast as the Predator. It also has improved imaging capabilities, enabling it to better distinguish objects on the ground, such as explosive packages and foot soldiers. The Reaper is still one of the most potent military drones in use and one of the most controversial weapons of war.[15]

LITERATURE SEARCH

A systemic literature search was performed to assess scientific work involving current medical applications of drones. The EBSCO (Elton B. Stephens Company) Discovery Service was used as the search engine. An advanced search was performed to identify sources that contained the phrases "drones," "UAV," "unmanned aerial vehicles," "UAS," and "unmanned aerial systems" as subject terms. The sources were arranged chronologically, and their titles were screened for relevance and selected if deemed applicable. Source types included magazines, academic journals, news articles, trade publications, and electronic resources. All sources published in the English language through April 2017 were included. Duplicate search results were excluded.

Next, sources were selected that discussed the application of drones in civilian sectors and were grouped into 7 broad categories: agriculture, environment and conservation, law enforcement and traffic, education, construction and industry, commercial shipping, and medicine (**Figure 1**). Both academic and nonacademic sources were accepted. Academic sources were defined as sources published in scholarly journals or proceedings from national conferences. Nonacademic sources were included in an effort to capture the latest information in reporting on how drone technology is currently being used. Sources that discussed the same application were included. From these articles, relevant literature was extracted.

An additional search was used to identify sources that contained the term "drone" in either the subject terms or title, and the word "medicine" in any aspect of the text. The purpose of this search was to isolate medical sources that may have been missed in the initial search. The paradigm used to process the sources from the initial search was applied, including magazines, academic journals, news articles, trade publications, and electronic sources in English up through April 2017. Search results were arranged in chronological order. Duplicate search results or articles that were found in the initial search were excluded. The sources pertaining to medical applications were further indexed into 3 major categories: public health/disaster relief, telemedicine, and medical transport (**Figure 2**).

Major themes within public health/disaster relief included mass casualty care, data collection, infectious disease, disaster relief, and emergency medicine. Within the category of telemedicine, descriptions included drones assisting in surgical procedures in simulated harsh environments, including the battlefield, and use of drones as telemedical devices in emergency settings. Medical supply and transport articles involved several subcategories, including delivery of medical goods, evacuation of patients, and commercial applications for infrastructure. This organizational framework is depicted in **Figure 3**.

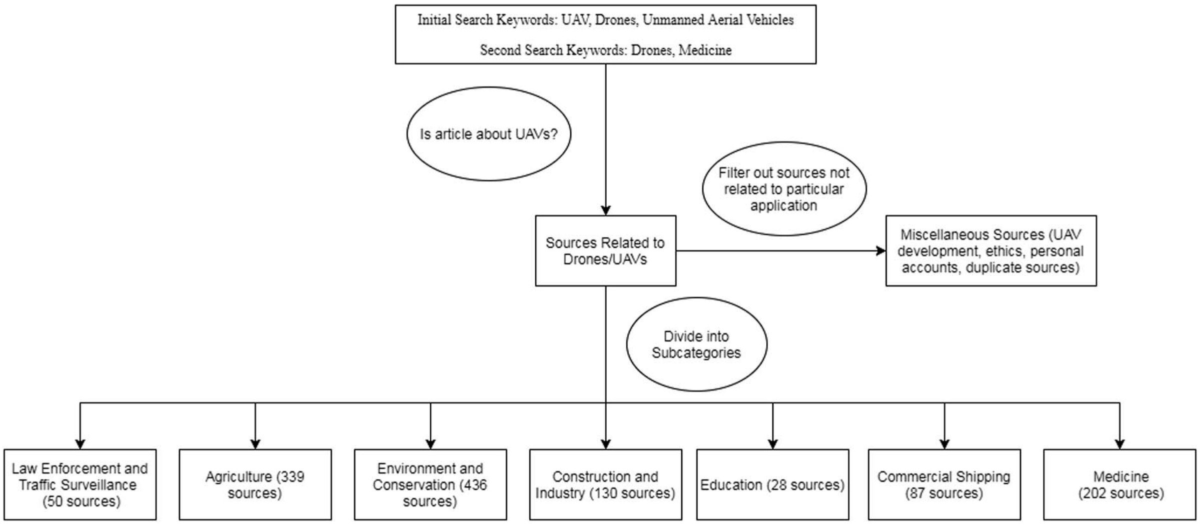

Figure 1. Initial literature search.

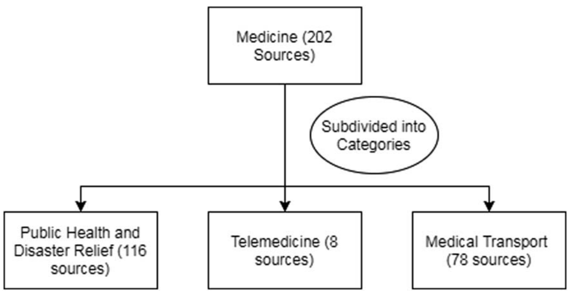

Figure 2. Medical literature search.

RESULTS

The initial search in the EBSCO database yielded 60,260 results. After titles and abstracts and irrelevant material were filtered, 1296 sources remained applicable. Within our first tier of major themes, there were 339 agricultural sources, 436 sources pertaining to environment and conservation, 130 sources to construction and industry, 50 sources to law enforcement and traffic, 28 sources in education, 87 sources in commercial shipping, and 159 sources within the medical literature (**Figure 1**). The second search for medical sources yielded an additional 43 articles, making the total medical sources 202. Within the medical literature, there were 116 articles relating to public health and disaster relief, 8 pertaining to telemedicine, and 78 involving medical transport (**Figure 2**).

Public Health and Medical Surveillance

Drones are used for surveillance of disaster sites, areas with biological and chemical hazards, and tracking disease spread. It has been shown that drones can gather information about the number of patients in need of care and triage in high-risk environments.[16] In 2013, drones were used after Typhoon Haiyon in the Philippines to provide aerial surveillance to assess initial damage of the storm and prioritize relief efforts.[17] In an effort to improve the efficiency of response teams, the National Health Service in England has investigated the use of drones to assess injuries related to chemical, biological, and nuclear materials.[18]

Drone technology has been used to detect health hazards, such as heavy metals, aerosols, and radiation. In a study from southern Italy, drones equipped with high-resolution photogrammetry software were used to accurately access and predict cancer risk from high level copper concentrations in agricultural areas.[19] Brady et al[20] demonstrated the ability of a quadrotor drone with a built-in sampling platform to accurately measure aerosol and trace gas levels within complex terrain. Through early detection, this system can prevent the spread of health hazards from pathogens. Along those lines, drone technology has also been used to detect radionuclides that are typical in nuclear accidents and map out radiation from uranium mines.[21,22]

Furthermore, the ability of drones to acquire real-time, high-resolution temporal and spatial information at low cost makes them viable for epidemiology research. Such a use involves monitoring deforestation, agricultural expansion, and other activities that alter natural habitats and ecological communities. Fornace et al[23] demonstrated the use of drones to characterize changing land and deforestation patterns in Malaysia that influence the zoonotic

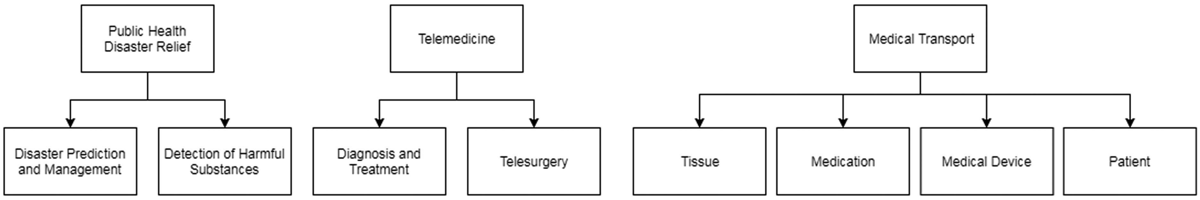

Figure 3. Subcategories of medical applications.

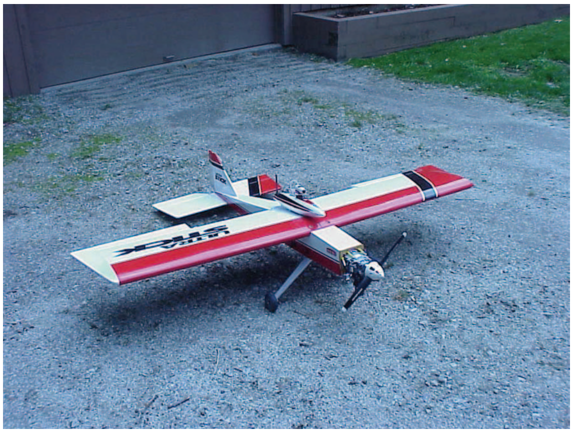

Figure 4. Rosser Instant Telecommunications Infrastructure Drone circa 1998–2000.

spread of malarial parasites. In another case study, Barasona et al[24] used drones to track the spatial distribution of tuberculosis-carrying large mammals in southern Spain. Recently, researchers have used drones with nucleic acid analysis modules to detect *Staphylococcus aureus* and the Ebola virus.[25]

Telemedicine

One of the most promising uses of drones is in the emerging field of telemedicine—the remote diagnosis and treatment of patients by means of telecommunications technology.[26] The key word in the definition of telemedicine is telecommunications. Unfortunately, communications necessary for telemedicine missions to remote, disaster-relief, or combat environments cannot depend on commercial networks. The idea of the establishment of Instant Telecommunication Infrastructure (ITI) using drones was discussed by the senior author (JCR) in Athens, Greece, in 1998 at the Yale /NASA Commercial Space Center Telemedicine Program **Figure 4**. The presentation showcased a drone platform that concentrated on providing communications for performing pre- and postoperative evaluations of patients and telementoring of certain surgical procedures in remote areas. Telementoring is the provision of remote guidance by an experienced surgeon or proceduralist to a less experienced colleague, with emerging procedures using computers and telecommunications.[27] Using this ITI concept, Harnett et al[28] demonstrated how drones can be used to establish a wireless communication network between the surgeon and a robot to perform telesurgery—the performance of surgical procedures using a robot, with the operator being located remotely from the site of the patient. In the study, the surgeon and robot were placed in tents ~100 meters apart. The surgeon was able to successfully operate the robotic arms to perform exercises simulating surgical maneuvers. More recently, researchers have expanded investigation to less extreme care scenarios. William Carey University College of Osteopathic Medicine tested a telemedical drone to deliver medical supplies and communication packages for emergency clinical scenarios to assist in providing care.[29]

Drones as Medical Transport Systems

Fast response times and the ability to navigate otherwise impassable terrain makes drones an attractive medical delivery platform. In 2007, researchers from the National Health Laboratory Service (NHLS) and Denel Dynamics (UAV division) tested a proof-of-concept unmanned system to transport microbiological samples more efficiently from rural clinics to NHLS centers for rapid Human Immunodeficiency Virus (HIV) testing. The results demonstrated the ability of drones to facilitate medical decision-making with prompt diagnosis.[30] In 2014, the Médecins Sans Frontières (MSF) evaluated a drone-based system for delivering laboratory samples to hospitals for tuberculosis testing. This trial demonstrated that drones could deliver viable laboratory samples in ~25% of the time it took to deliver the samples by land.[31] Other research has shown that sample integrity from stationary blood samples compared to drone-transported blood samples is similar.[32,33]

The first government-approved drone medical delivery within the United States involved a clinic in rural Virginia. The drones served to expedite the drug delivery process, thus improving patient care.[34] Similarly, the United Nations Population Fund and the Dutch government addressed access to women's health clinics in Ghana with drones. They effectively delivered contraceptives and other gynecological supplies to Ghanaian women in need.[35] The United States Postal Service recently partnered with Zipline to evaluate the delivery of medications, blood, and vaccines in Rwanda.[36] Similar projects have been initiated in other developing countries.[37,38]

In the field of emergency medicine, drones have been used to deliver automated external defibrillators (AEDs) to those aiding individuals who are in cardiac arrest. Researchers from Delft University in the Netherlands showed how drones can facilitate AED delivery anywhere within a 1.2-square-mile radius in <2 minutes.[39] A computer-based simulation study out of Salt Lake County, Utah, demonstrated that properly stationed drones can reach 96% of the county's population in less than 1 minute. Conversely, traditional ambulance response times achieved this result in only 4.3% of cases.[40] Unfortunately, current systems are still riddled with problems, such as high collision rates, airspace regulations, and injury control. Therefore, more studies must be performed to optimize their efficiency and performance.[41]

The military has led the investigation of the utility of drones for patient transport. The U.S. Army Medical Research division demonstrated the possibility of using VTOL drones to extract injured soldiers while avoiding airspace collisions. However, their report concludes that there is still a lack of concrete guidelines and standards regarding the physiological impact of flight on patient health and safety.[42] A 2015 demonstration by Kaman Aerospace in Connecticut successfully used coordinated unmanned air and ground vehicles to respond to a simulated distress call reporting a casualty in the field. Both unmanned systems were operated by a single person using an android tablet. An unmanned ground vehicle (UGV) was sent to assess the situation. Subsequently, a drone was sent to pick up a mannequin and transport it back to base.[43]

CONCLUSION

Despite the accelerating maturation of applications in media, agriculture, infrastructure inspection, and other fields, the evolution of medical applications of drone technology has been slower to develop. However, it must be considered that medical applications are more challenging because the urgency of clinical situations often does not allow control of date, time, and location. We must accelerate research efforts related to airspace integration, safety, response time, participation expansion, and privacy best practices. Under the Obama administration, the Office of Science and Technology Policy (OSTP) announced new steps, sustained by public and private support, to promote the safe integration and innovative adoption of drones. These federal executive actions will greatly assist the expansion of the industry and may assist in the cultivation of medical applications. Most notably, the Department of Transportation and the FAA's "Small UAS" rule will provide national guidelines for the operation of nonrecreational unmanned aircraft under 55 pounds.[44]—a big step forward, because the use of this platform is a very fertile area for medical applications.

Three other actions have placed drone use on the national agenda. In February 2015, President Obama issued a Presidential Memorandum titled: Promoting Economic Competitiveness While Safeguarding Privacy, Civil Rights, and Civil Liberties in Domestic Use of Unmanned Aircraft Systems.[45] In May 2016, FAA Administrator Michael Huerta announced the FAA's Drone Advisory Committee—a broad-based, long-term advisory committee that will provide the FAA with advice on key unmanned aircraft integration issues by helping to identify challenges and prioritize improvements related to this emergent technology.[46] Subsequently, in June 2016, the OSTP announced the White House Future of Artificial Intelligence Initiative to ensure smart policy-making on emergent technologies, such as drones and other intelligent platforms.[47] Furthermore, there has been intense focus by private and public and federal and state sectors aimed at nurturing industry progression by supporting initiatives to advance safety and industry expansion and increase public awareness and participation[48] (**Table 1**).

In the spirit of these 4 designated areas of focus, there are some noteworthy recent projects that deserve commentary. Drones must continue to expand their reach into STEM education. An example is the DroneSTEM program, an award-winning innovative approach that deconstructs elementary school science curricula and reconstructs them with validated pop culture icon educational assets such as drones, video games, music, and cinema, along with surgical simulation, to increase student engagement and state test scores in science.[49] This approach, at its core, develops skills and generates interest and cognitive competence with drones while expanding the participation pool.

In times of natural or manmade disasters, it is essential that we incorporate drones as an important emergency medical response asset. The establishment of a Drone Civil Air Patrol Wing (DCAPW) could operate under the current organization and command structure of the Civil Air Patrol (CAP). The CAP is a volunteer, federally supported, nonprofit corporation that serves as the official civilian auxiliary

Table 1.
Federal and State Industry Expansion Initiatives[48]

Safety	Industry Expansion	Public Awareness	Expanding Participation
Chartering of a UAS Safety Team to assist rulemaking to enable additional UAS operations over people.	The National Science Foundation (NSF) is committing $35 million in funding over 5 years for UAS research.	Exploring the public's views on using unmanned aircraft for the delivery of mail or packages.	The Drone Racing League (DRL) has developed safety solutions for drone racing operations
NASA is now tasked with enabling the safe integration of UAS through standards generation and interagency collaboration.	Empire State Economic Development Agency has committed to expand the UAS industry.	The Commercial Drone Alliance has been established to inform the public about UAS integration.	The Women of Commercial Drones and the Commercial Drone Alliance support greater participation of women and girls in aerial robotics and the drone industry.
NASA's Aeronautics Research Mission Directorate meant initiate new research to develop standards for Detect and Avoid and Command and Control for UAS.	Northern Plains UAS Test Site in North Dakota will expand its UAS testing portfolio to assist in rapid prototyping and approval of new UAS payloads.	Sinclair Broadcast Group, Association for Unmanned Vehicle Systems International (AUVSI) and the Academy of Model Aeronautics (AMA), "Know Before You Fly" Public Service Announcements to educate the public about safe unmanned aircraft operations.	DroneBase and Drones & Good enable job placement for veterans with free drone pilot training.
Establishment of a joint NASA and FAA data exchange bureau.		Intel and PrecisionHawk Future of Privacy Forum Report "Drones and Privacy by Design: Embedding Privacy Enhancing Technology in Unmanned Aircraft."	4-H's National Youth Science Day and DJI encourages STEM youth engagement through UAS
Project Wing: The operational deployment of an experimental context for evidence-driven policymaking and safe operation			
Precision Hawk: An initiative meant to facilitate early release of research and test results meant to improve safety			

NASA-National Aeronautics and Space Administration; UAS- Unmanned Aircraft System; FAA-Federal Aviation Administration; STEM-Science Technology Engineering Math.

of the USAF with congressional oversight. It served key homeland security missions during WWII, including antisubmarine patrol and warfare, border patrols, and courier services.[50] The DCAPW could train personnel and operate a large force of drones that are configured to carry out various disaster-initiated medical missions. For this concept to become a reality, the bureaucratic inertia associated with airspace restrictions, permission of operation, and avoidance of collisions with full scale aircraft must be addressed. With the CAP already under USAF and congressional oversight, the mitigation of such obstacles could be more efficient. In view of the plethora of recent activity prompted by executive actions and aggressive public–private sector involvement and funding, the foundation has been laid for drone applications in medicine to be investigated and deployed to enhance healthcare delivery worldwide.

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