Center for the Study of the Drone

Bard College

Drone Sightings and Close Encounters: An Analysis

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The Center for the Study of the Drone at Bard College is an interdisciplinary research institution founded in 2012 that examines the novel and complex opportunities and challenges presented by unmanned technologies in both the military and civilian sphere.

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Executive Summary

This report represents the result of a comprehensive and detailed analysis of incidents involving unmanned aircraft and manned aircraft in the U.S. National Airspace System. We have collected records of 921 incidents involving drones and manned aircraft in the national airspace, dating from December 17, 2013 to September 12, 2015. We have organized these reports into two categories: Sightings, incidents in which a pilot or an air traffic controller spotted a drone flying within or near the flight paths of manned aircraft though not posing an immediate threat of collision, and Close Encounters, where a manned aircraft came close enough to a drone that it met the Federal Aviation Administration's definition of a "near midair collision" or close enough that there was a possible danger of collision, even if an exact drone-to-aircraft distance was not reported. By these criteria, 35.5 percent of the incidents were Close Encounters, and 64.5 percent were Sightings. We found that over 90 percent of all incidents occurred above 400 feet, the maximum altitude at which drones are allowed to fly. A majority of the total incidents occurred within five miles of an airport (which is also prohibited airspace for all drones, regardless of the altitude at which they are flying). Incidents within five miles of airports occurred at lower altitudes than incidents beyond five miles of an airport. Our findings indicate that incidents largely occur in areas where manned air traffic density is high and where drone use is prohibited. We counted 158 incidents in which a drone came within 200 feet or less of a manned aircraft (two-thirds of all Close Encounters in which a concrete drone-to-aircraft proximity is given), 51 incidents in which the proximity was 50 feet or less, and 28 incidents in which a pilot maneuvered to avoid a collision with a drone. One hundred and sixteen of the Close Encounters involved multiengine jet aircraft, 90 of which were commercial aircraft (the majority of which have the capacity to carry 50 or more passengers). We also counted 38 Close Encounter incidents involving helicopters. The reports do not always clearly identify the type of drone involved in incidents, but of the 340 drones that were identified in the reports, 246 were multirotors (i.e. quadcopters, hexacopters, etc.) and 76 were fixed-wing. The locations with the highest number of incidents were large metropolitan areas. Two-thirds of incidents happened between 10 a.m. and 6 p.m., local time.

Introduction

Around noon on a clear February day, Delta Air Lines Flight 1559 was on the last leg of a six-hour flight to Los Angeles from Honolulu. Eight miles out from the airport, as the Boeing 757 jet descended out of 3,000 feet on final approach to runway 25 Left, the first officer prepared to radio the air traffic controllers at Los Angeles Tower for instructions. Before reporting in, however, an object in the distance caught the attention of the pilot. “At first I thought it was a large bird soaring towards us,” the first officer wrote in a report following the incident. “But as it passed outside of the right forward first officer's (FO) window, I very clearly saw a large square-shaped bright red drone with black accents and black propellers.” The drone flew by, passing 150 feet to the right of the jet. The first officer radioed in to the tower, warning that a drone had been sighted within the final approach to LAX.[1]

In the report filed with the NASA Aviation Safety Reporting System, a voluntary and confidential forum established to improve aviation safety, the Delta pilot wrote that while the encounter was “uncomfortably close,” it was not clear to the pilot what the crewmembers or the air traffic controllers could have done to prevent the incident from taking place. With the increasing frequency of reported close encounters between drones and manned aircraft, many in the aviation safety community and beyond are asking the same question: Why are these incidents occurring and what can be done to prevent a potentially catastrophic accident?

In order to help address these questions, we have compiled and analyzed a detailed database of incidents involving drones in U.S. National Airspace System. Our dataset consists of Federal Aviation Administration and Department of the Interior reports submitted by pilots and air traffic controllers over the period from December 2013 to September 2015. The FAA reports, which make up the bulk of the dataset, were released to the public in two stages. On Nov. 26, 2014, the FAA released reports from February to November of that year in response to requests from various media outlets including The New York Times and The Wall Street Journal.[2] On Augus 21, 2015, the FAA released reports from November 2014 to August 20, 2015 after an FAA employee leaked several hundred reports to The Washington Post.[3] Our dataset also includes one report from prior to February 2014 and six incidents that occurred after Aug. 20, 2015.

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1 NASA, Aviation Safety Reporting System, Incident Report, (ACN: 1242105), February, 2015. Accessed November 29, 2015. http://asrs.arc.nasa.gov/

2Jack Nicas, "Increase in Drones Spotted Near Aircraft," *Wall Street Journal*, November 26, 2014, Tech. Accessed

2Jack Nicas, "Increase in Drones Spotted Near Aircraft," *Wall Street Journal*, November 26, 2014, Tech. Accessed
December 5, 2015. http://www.wsj.com/articles/faa-reports-more-aircraft-drone-near-misses-1417025519.

3Craig Whitlock, "FAA records detail hundreds of close calls between airplanes and drones," *The Washington Post*, August 20, 2015, National Security. Accessed December 5, 2015. https://www.washingtonpost.com/world/national-security/faa-records-detail-hundreds-of-close-calls-between-airplanes-and-drones/2015/08/20/5ef812ae-4737-11e5-846d-02792f854297_story.html.

In combination, the two FAA releases produced over 1,000 incident reports. However, many of these reports did not involve drones interfering in the airspace in a way that could pose a risk to manned aviation (for example, some reports were for drones flying near stadiums, which is also prohibited by the FAA). Some reports were duplicates of records that had already been submitted. There were other inconsistencies. A few reports indicated the local time of an incident, while others were recorded in Zulu Time. Other reports contradicted themselves, or included obvious mistakes. One incident near Green Airport in Rhode Island (PVD) was recorded as having occurred at Plovdiv Airport in Bulgaria (PDV). We have worked through every report to adjust these inconsistencies. The result is a database that is more expansive, reliable, and detailed than anything previously available.

In order to draw a quantitative picture of the issue, we have extracted data from each of these reports. These data points include incident altitude, proximity to airports, drone-to-aircraft proximity, manned aircraft type, drone type, and incident time. Our findings are described in Chapter II.

Why should these reports be analyzed?

There are several reasons why it is important to try to draw actionable generalizations from reports of incidents involving drones and manned aircraft. First, such incidents are becoming much more common. In May 2014, 10 incidents were reported to the FAA; in May of this year, there were 100 incidents. Chapter I offers a background on the growing rate of incidents. As the rate of incidents continues to grow, the need for solutions becomes more urgent. In the period after our dataset ends, incident rates have remained high. An FAA spokesperson informed the Center for the Study of the Drone that there have been at least 380 incidents since Aug. 21, 2015: 74 in the final ten days of August, 127 in September, 137 in October, and 42 in November as of the 16th. The stakes of these incidents are potentially significant. As we discuss in Chapter IV, a collision between a drone and a manned aircraft could lead to a potentially catastrophic incident. Given that the FAA has not yet established and implemented its regulations for drone use within the U.S., incidents that occur in these months can have a direct impact on the rulemaking process. Indeed, when the Department of Transportation convened a task force in October to develop recommendations for a drone registration system, it was in part a direct response to the growing rate of incidents involving drones in the national airspace. An intelligence official at a federal agency, who asked that their name not be published, described how a catastrophic incident involving a drone and a manned aircraft would provoke a concerted regulatory whiplash that could seriously hamper growth in the industry. Finally, we believe that stakeholders who are seeking to develop solutions to airspace conflicts involving drones now have, in these reports, information that could potentially be helpful in pointing to such solutions. A summary of solutions currently being developed is provided in Chapter V.

There is some disagreement about the reliability of these reports, as well as the ways in which they should be interpreted. Some analyses might point to a set of dire conclusions, while another analysis might paint a less severe picture of the actual likelihood that such incidents might result in an accident. It is important not to downplay the threat posed by drones within the airspace, but it is just as important not to exaggerate the proportions of that threat. We have aimed for an entirely inquiry-driven approach to the data, and our methodology is described in Chapter III. Given these stakes, we have endeavored to treat the source material carefully and to be transparent about our methodology. It is our hope that, as a result, this report can serve as a reliable source for stakeholders who are seeking to understand this issue more thoroughly.

During the preparation of this report we have turned to a number of top experts for input. We would like to thank Javid Bayandor and his entire team at the Crashworthiness for Aerospace Structures and Hybrids (CRASH) Lab at Virginia Tech University; Ella Atkins, associate professor of aerospace engineering at University of Michigan; R. John Hansman, Jr., director of the MIT International Center for Air Transportation; and Thomas Keenan, director of the Human Rights Project, Bard College. We would also like to thank Madi Garvin and Mikey Gray for their editorial support.

I. Background to the Issue

- Drone Sightings and Close Encounters in the national airspace are a recent challenge.
- Cheap, commercially available unmanned aircraft are capable of exceeding the FAA's guidelines and rules for safe use.
- It is possible to operate these systems without knowledge of airspace rules and norms.
- The rate of incidents has been increasing since 2013.

The challenges posed to aviation safety by unmanned aircraft in the national airspace are relatively new. Prior to the meteoric rise in popularity of consumer multirotor models and commercial drones, most of the unmanned aircraft in the airspace were flown by a dedicated community of model aviation hobbyists. The modelling community has existed for generations—the Academy of Model Aeronautics (AMA), the largest association for model aircraft hobbyists, was formed in 1936, making it older than the Federal Aviation Administration. AMA members observe an extensive set of rules and regulations established by the organization. According to its website, the AMA has over 2,500 flying clubs across the country, which provide members with dedicated spaces from which to fly.

The self-regulating nature of the AMA has allowed it to operate for decades without hard and fast regulations. In 1981, the FAA issued Advisory Circular 91-57, a set of voluntary guidelines for model aviation hobbyists, such as staying under 400 feet and at a safe distance from airports.[4] Given the relatively small and controlled scale of model aircraft flights, there was little need on the part of the federal government to closely police the modelling community. Under this arrangement, incidents involving remote control aircraft in the national airspace were exceedingly rare.

Over the past decade, this all began to change. As the size and cost of components like gyroscopes, autopilot systems, and cameras dropped, advanced model aircraft equipped with high-definition video cameras and capable of semi-autonomous and autonomous flight became cheaper to buy or build—and easier and more desirable to fly. The popularity of consumer models like the Parrot AR.Drone, first released in 2010, and the DJI Phantom, released in 2013, skyrocketed. In 2014, consumers bought up to 400,000 DJI-made units and, during the 2015 holiday season alone, some 1,000,000 drones are expected to be sold.[5] The availability and affordability of off-the-shelf drones like the Phantoms, which today run for as little as a few hundred dollars, means that new users could start flying immediately, bypassing the education process and rules associated with participation in the model aeronautics community.

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[4] Federal Aviation Administration, Advisory Circular 91-57, Model Aircraft Operating Standards, Misc. Doc. (1981). Accessed December 6, 2015. http://www.faa.gov/documentLibrary/media/Advisory_Circular/91-57.pdf.

[5] Karp, Aaron, "FAA warns of 'a million drones under people's Christmas trees,'" *ATW Online*, September 28, 2015. Accessed December 5, 205. http://atwonline.com/technology/faa-warns-million-drones-under-people-s-christmas-trees.

In response to the proliferation of drones, the FAA has doubled down on its rules and guidelines for unmanned aircraft use. In September 2015, the FAA updated Advisory Circular 91-57 with stricter guidelines, including a provision affirming its right to "pursue enforcement action against persons operating model aircraft who endanger the safety of the National Airspace System."[6] Cheap, commercially available drones are capable of far exceeding the FAA's 400-foot ceiling for remote control aircraft, making it relatively easy for users without detailed knowledge of airspace rules to potentially find themselves operating a drone within the flight path of a manned aircraft. This issue is compounded by the fact that U.S. airspace is extremely busy. Phoenix Sky Harbor International Airport, for example, has an average of 1,183 incoming and outbound flights every day, according to FlightAware[7] (in our database, eight incidents were reported in Phoenix alone). Drone operators without knowledge of airspace norms may not be aware that the sky directly above them is frequented by aircraft flying at low altitudes. Moreover, regulators and air traffic controllers are concerned that drone operators may not be able to see and avoid other aircraft, an essential capability for any pilot.

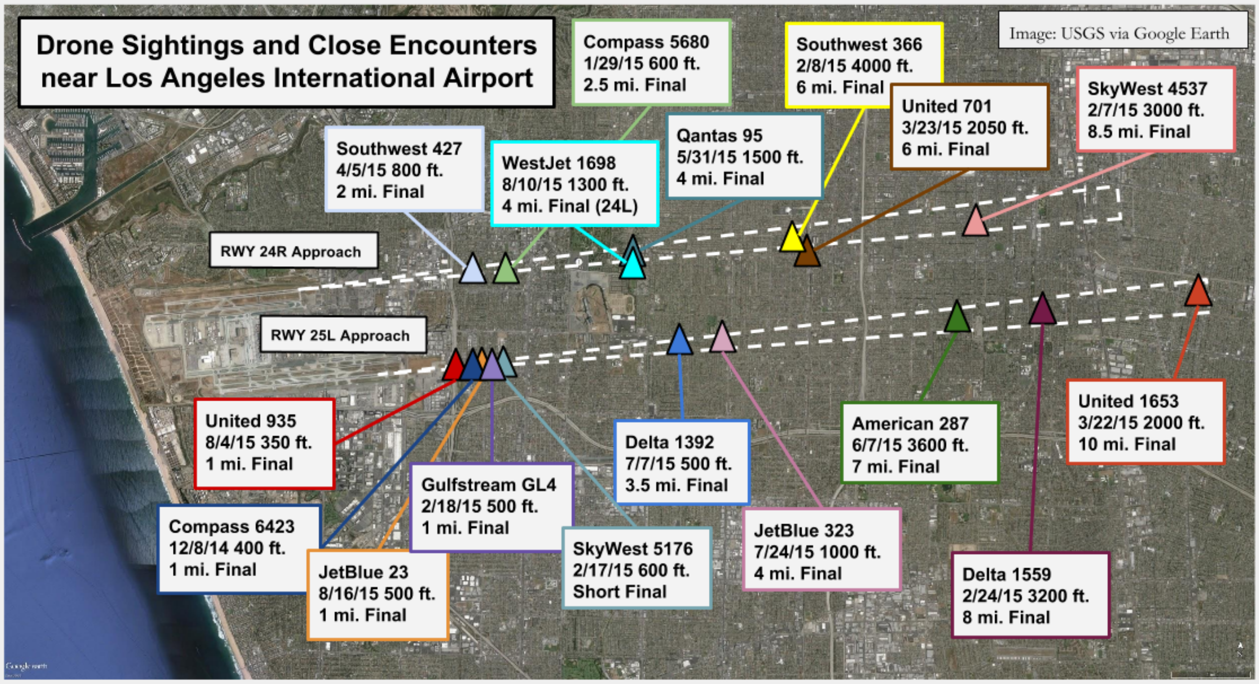

Figure I.1 Drone Sightings and Close Encounters around LAX — Center for the Study of the Drone at Bard College

Note: The locations of these incidents are an approximation based on approach patterns and reported altitudes and distances.

[6] Federal Aviation Administration, Advisory Circular 91-57A, Model Aircraft Operating Standards, Misc. Doc. (2015). Accessed December 6, 2015. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_91-57A.pdf
[7] "Phoenix Sky Harbor Intl Airport (Phoenix, AZ) KPHX Overview," FlightAware, accessed December 6, 2015, http://flightaware.com/resources/airport/KPHX/summary.

Reports of incidents involving drones in the airspace began making regular headlines in 2013. In March of that year, an Alitalia long-haul airliner pilot spotted a drone over Brooklyn while on approach to New York's John F. Kennedy International Airport.[8] As the airspace became more crowded with model aircraft and consumer drones, the FAA began to receive a growing number of reports from air traffic controllers and pilots of drones operating near or within the flight paths of manned aircraft.

Why the spike in incidents?

"Because the issue of drones has been so much in the news, you have this feedback process, where you tend to get an increase in reporting because of the topic. At the same time, you clearly do have an increase in the number of vehicles being operated."
R. John Hansman, director of the MIT International Center for Air Transportation

Since August 21, 2015, which is where our data ends, the number of reports has continued to remain high. According to an FAA spokesperson, there were 137 reports in October 2015, alone. Referring to the general uptick in incidents over the past two years, the spokesperson explained, "You are hearing about more incidents due to a combination of factors: There are more drone users and there is also more awareness by the pilot and air traffic controller communities who report incidents." The reports of drone sightings have come from a wide variety of participants in the national airspace system, including air traffic controllers, commercial and general aviation pilots, and government personnel.

The public concern around the safety challenges presented by the integration of drones into the national airspace prompted a hearing on aviation safety at the House Committee on Transportation and Infrastructure, Subcommittee on Aviation, on Oct. 7, 2015.[9] One of the issues raised by lawmakers was the challenge of identifying the incidents that are significant, and defining what exactly constitutes a near miss between a drone and a manned aircraft. "We don't know what we're talking about because we can't even quantify it," Rep. Todd Rokita said. "There are millions of birds too." Indeed, many of the reports indicated few signs of immediate danger posed by a drone to the manned aircraft. Furthermore, the reliability of the reports has also drawn scrutiny. The dynamic and high-pressure environment that is the cockpit of an aircraft can make it difficult to generate highly detailed and fully reliable accounts of incidents. When a pilot spots a drone at 3,000 feet, many other factors are competing for their attention, leading to irregular or approximated reporting.

Following the FAA's release of the database of pilot reports in August, critics blamed the FAA and the media for sensationalizing the incidents—which the FAA had described in a press release as

[8]Muskal, Michael. "FAA investigating report of drone aircraft over JFK airport." *Los Angeles Times*, March 5, 2013. Accessed December 6, 2015. http://articles.latimes.com/2013/mar/05/nation/la-na-nn-faa-drone-jfk-airport-20130305.

[9] *Ensuring Aviation Safety in the Era of Unmanned Aircraft Systems: Hearings Before the Subcommittee on Aviation* (2015) (statement of Chairman Frank LoBiondo). Accessed December 6, 2015. http://transportation.house.gov/calendar/eventsingle.aspx?EventID=399335.

"close calls"[10]—and it was argued that birds and even lasers pose a greater threat to manned aviation than drones. Richard Hanson, the director of government and regulatory affairs at the Academy of Model Aeronautics, was particularly outspoken against misrepresentations of the data. "Exaggerating and mischaracterizing the data makes it impossible to assess the magnitude of the situation and appropriately address the risks involved," Mr. Hanson argued in written testimony submitted to the subcommittee on Oct. 7.[11] Some weeks earlier, the AMA conducted its own study of the FAA's data and concluded that the number of incidents that constituted a near-miss were drastically lower than the numbers reported by the media. By excluding the reports that did not include mentions of an NMAC or evasive maneuvers, the AMA found only 3.5 percent of the reports constituted a near-miss incident.[12]

Nevertheless, the rise in the number of drone sightings and encounters has made these incidents a highly visible and potentially concerning issue, drawing repeated calls for action from lawmakers like Sen. Chuck Schumer and Sen. Dianne Feinstein, and these reports are the richest source of data on the issue.[13] By undertaking a close examination of the available data and scientific studies, this report seeks to address these concerns and provide a balanced reading of the potential challenges presented by unmanned aircraft integration in the national airspace. We have carefully reviewed each of the incident reports in our database to ensure that they meet our criteria for either a Close Encounter or a Sighting, and an intelligence official at a federal agency has cross-checked these reports against non-public records of airspace incidents to ensure that no significant incidents from this period are missing from our dataset.

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[10]Federal Aviation Administration. "Pilot Reports of Close Calls With Drones Soar in 2015." News release. August 12, 2015. https://www.faa.gov/news/updates/?newsId=83445.

[11]*Ensuring Aviation Safety in the Era of Unmanned Aircraft Systems: Hearings Before the Subcommittee on Aviation* (2015) (statement of Richard Hanson). Accessed December 6, 2015. http://transportation.house.gov/uploadedfiles/2015-10-07-hanson.pdf.

[12]Academy of Model Aeronautics. *A Closer Look at the FAA's Drone Dat*a. Accessed December 6, 2015. http://www.modelaircraft.org/gov/docs/AMAAnalysis-Closer-Look-at-FAA-Drone-Data_091415.pdf.

[13] "Feinstein Introduces Bill to Improve Safety of Consumer Drones." News release. June 18, 2015. Accessed December 6, 2015. http://www.feinstein.senate.gov/public/index.cfm/2015/6/feinstein-introduces-bill-to-improve-safety-of-consumer-drones

II. Findings

Our methodology is discussed at length in Chapter III.

We divided incidents into two categories: Close Encounters and Sightings. We defined Close Encounters as incidents where a drone comes within 500 feet of a manned aircraft, when a pilot declares a "Near MidAir Collision," when a pilot takes evasive action, or when the pilot uses descriptive language that indicates the drone as being dangerously close (for example: "almost hit" or "passed just above"). A Sighting, on the other hand, is when a drone is spotted above its legal ceiling or in the vicinity of an airport or aircraft, but does not pose a clear potential for a collision. Based on these definitions, of the 921 incidents in the database 327 were Close Encounters and 594 were Sightings.

- Eight times as many incidents were reported in the first seven months of 2015 than in the same period in 2014.
- Three out of five incidents occurred within the no-drone zone of an airport.
- Only about one in ten incidents took place at or below 400 feet.
- One in five reported drone-to-aircraft proximities of Close Encounters was less than 50 feet.
- In about one out of 12 Close Encounters, pilots took evasive action to avoid the drone.
- Incidents are more than three times as likely to involve multirotor drones than fixed-wing drones.
- Over a quarter of Close Encounters involved multiengine commercial jet aircraft.
- Two thirds of incidents occur between 10:00 a.m. and 6:00 p.m.
- New York City and Newark was the most common locations for incidents, with a total of 86.

The rate at which incidents were reported grew rapidly over the period covered by our database. The database includes 213 incidents from 2014 and 707 incidents from 2015 (our data includes one incident from before 2014). There were 70 incidents in the first seven months of 2014, and 585 during the first seven months of 2015. A total of 480 incidents, or 52.1 percent of all reported incidents, occurred between May and August of 2015 (86 incidents were reported in the same period in 2014). There were 74 incidents in the final ten days of August 2015, making it the month with the most incidents on record (a total of 193). There were 127 incidents in September, 137 incidents in October, and 42 incidents in the first 16 days of November.

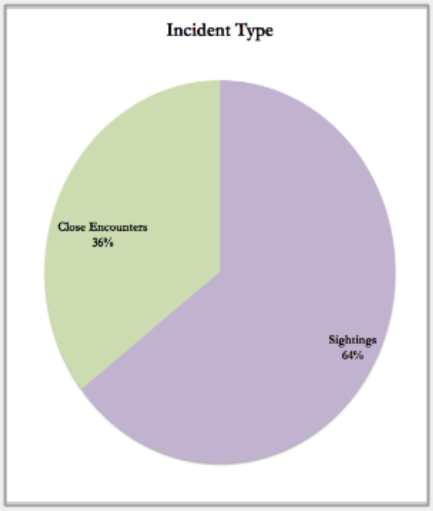


Figure II.1 Incidents by Type

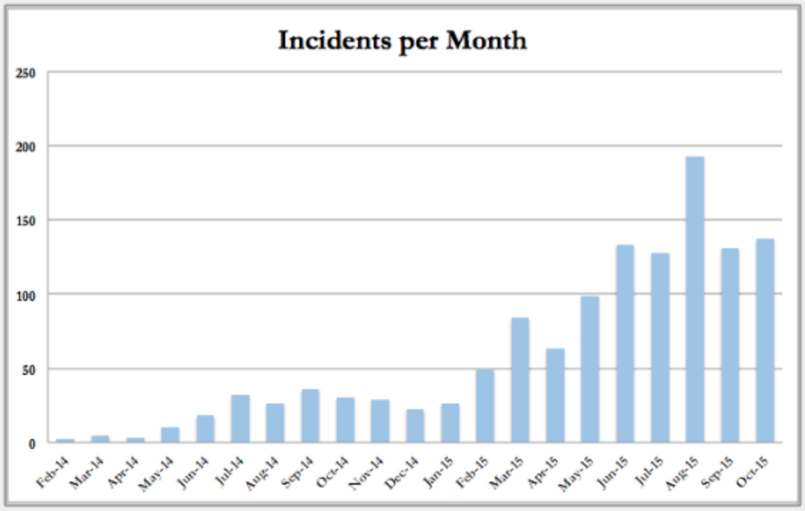


Figure II.2 Incidents by month

The FAA prohibits the use of unmanned aircraft within five miles of any airport in the U.S. without permission from air traffic control. This is because manned aircraft fly at low altitudes, sometimes for several miles, while on final approach and during take-off. Of the 665 incidents in which a distance from an airport was recorded, 391, or 58.8 percent, occurred within five miles, and 273, or 41.2 percent, occurred beyond five miles from the nearest airport. Some incidents occurred up to 30 miles from the nearest airport. In other words, in about two out of five cases, a drone was not within an airport's no-fly zone when it interfered with manned air traffic. The average distance from an airport was 6.86 miles.

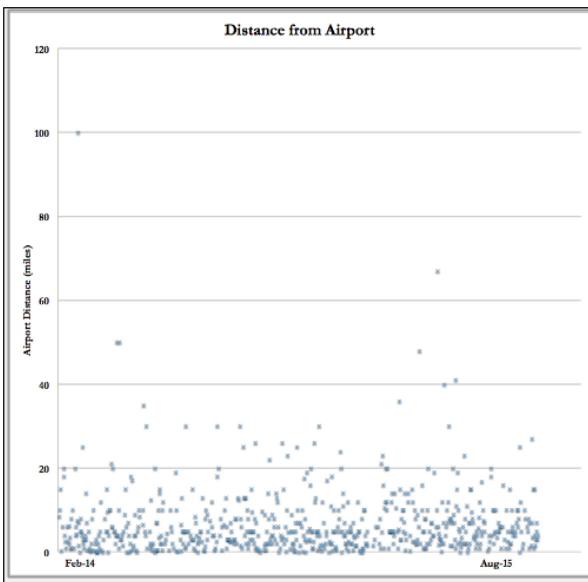


Figure II.3 Incident distance from airport

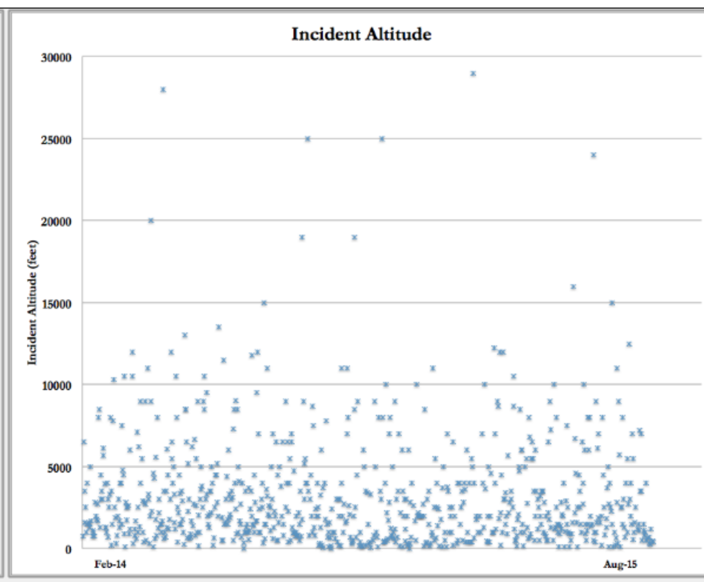


Figure II.4 Incident altitude

Most incidents occurred above the FAA's 400-foot ceiling for unmanned aircraft. Of the 785 incidents for which an altitude was reported, 77, or 9.8 percent of all incidents with a reported altitude, occurred at or below 400 feet, and 708 incidents, or 90.2 percent of those with a reported altitude, occurred above 400 feet. 484 incidents occurred between 400 feet and 4,000 feet, and another 224 incidents occurred above 4,000 feet. The highest recorded altitude for an incident was 29,000 feet, a Sighting at Alma, Ga. on May 11, 2015. The average altitude for incidents was 3,278.3 feet, and the median altitude was 2,100 feet. *Note: While most incident reports are likely to record an Above Ground Level (AGL) altitude, some incidents in the database indicate an Above Mean Sea Level (MSL) altitude or a Flight Level (FL), which is based on barometric pressure.*

Generally, incidents beyond five miles of an airport occurred at much higher altitudes than incidents within five miles of an airport. The average altitude of incidents with a recorded airport distance of more than five miles was 5,032.77 feet. The average altitude of incidents that occurred within five miles of an airport was 1,887.36 feet.

We identified 241 reports that indicated a drone-to-aircraft proximity of less than 500 feet, all of which we classified as Close Encounters. Of these incidents, 158, or 65.6 percent, indicated a proximity of less than 200 feet. In 51 incidents, the drone-to-aircraft proximity was 50 feet or less. The average Close Encounter proximity was 217 feet and the median proximity was 150 feet. *Note: When flying at high speeds, it can be difficult to judge the distance between yourself and another object. Therefore, proximities indicated in the reports, when provided, must be considered as approximate values.*

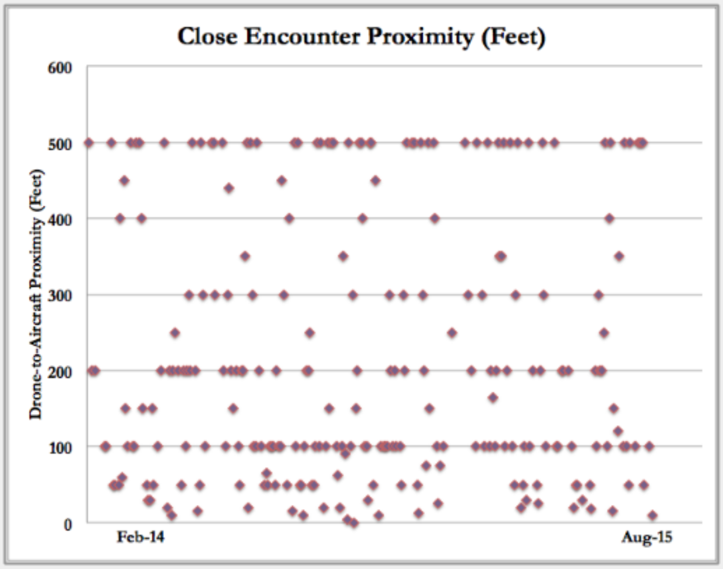


Figure II.5 Close Encounter drone-to-aircraft proximity

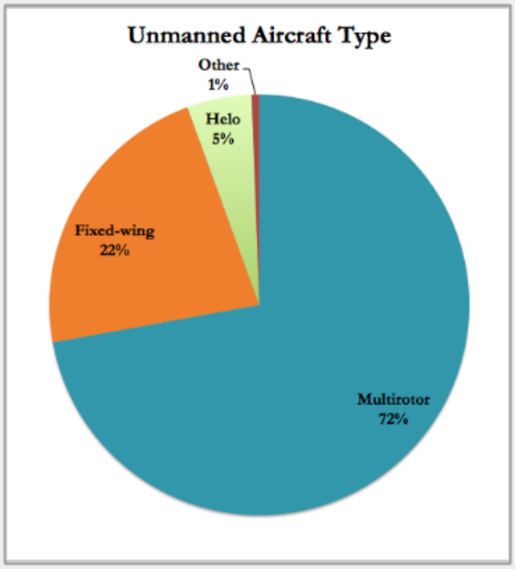


Figure II.6 Drone type in Sightings and Close Encounters

We counted 28 incidents in which pilots reported taking evasive action to avoid a drone. In some incidents, the report simply states that "no evasive action was taken," and does not specify whether evasive action might have been advisable. In other reports, pilots recorded that no evasive action was necessary, even in instances where the proximity to the drone was less than 500 feet. In certain cases, it is possible that no evasive action was taken because a pilot did not have sufficient time to react to the drone. For example, in a Close Encounter on June 13, 2015 over Charlottesville, Va., the pilot reported "that he did not have time to make any evasive maneuvers" (the drone reportedly came within 25 feet of his aircraft.)

For the incident reports that contained enough identifying material, we have classified the types of drones that were reported. Of the 341 incidents in which we were able to identify the drone type, 246 incidents involved multirotor drones, 76 involved fixed-wing drones, and 17 involved helo-type drones (one incident identified the unmanned aircraft as "mini blimp" and another reported a "model rocket").

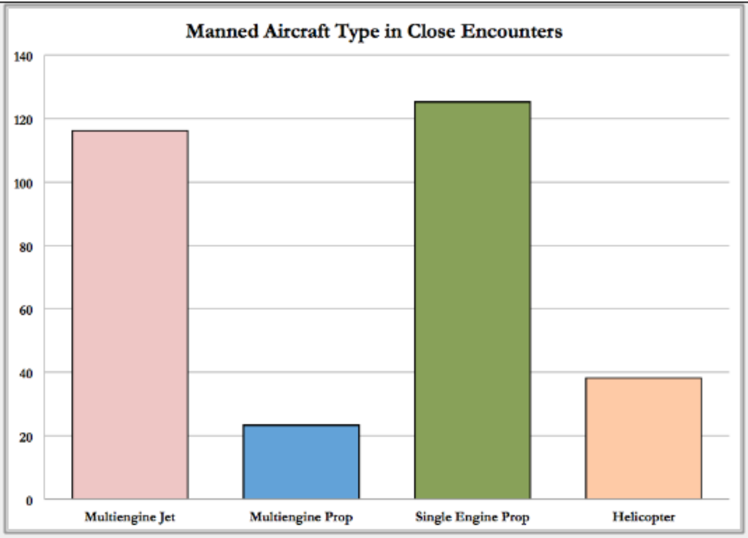


Figure II.7 Manned aircraft type in Close Encounters

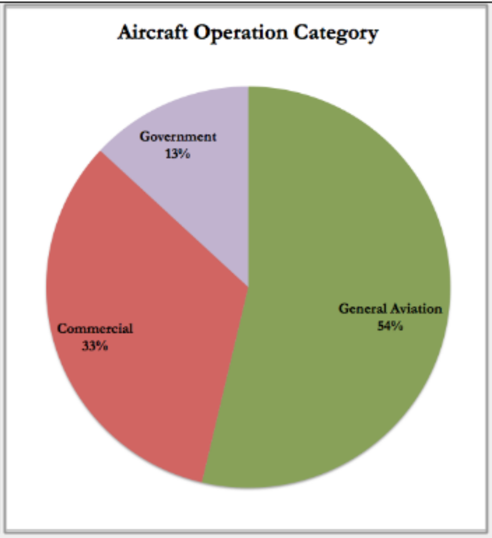


Figure II.8 Manned aircraft operation category in Close Encounters

We analyzed the data to determine what kinds of manned aircraft were involved in the incidents that we counted as Close Encounters. This information is important, as a collision between a drone and a single engine propeller-driven aircraft will be different from a collision between a drone and a multiengine jet. 116 Close Encounters involved multiengine jet aircraft (which range in size from small corporate jets to large commercial airliners), 125 involved single engine prop aircraft, 23 involved multiengine prop aircraft, and 38 involved helicopters. A small number of reports did not identify the aircraft.

We also analyzed whether manned aircraft were operated privately, commercially, or for the government (which includes the U.S. military). We found that 160, just over half of recorded manned aircraft, involved general aviation aircraft, which includes private and chartered aircraft; 99 involved commercial aircraft; and 39 involved government aircraft, such as military transport planes, emergency services helicopters, and firefighting aircraft. We found that 90 Close Encounters, or 27.5 percent, involved commercial multiengine jets.

We analyzed the reported time of all incidents to find out when incidents are most likely to occur. Of the 877 incidents for which a time was reported, 283 (32.3 percent) occurred between 10 a.m. and 2 p.m. local time, 298 (34 percent) of incidents occurred between 2 p.m. and 6 p.m., and 194 (22.1 percent) occurred between 6 p.m. and 10 p.m. The remaining 11.7 percent of incidents occurred between 10 p.m. and 10 a.m.

The location that had the most incidents was New York City, with 83 incidents (including nine incidents around Newark Airport, in New Jersey), followed by Los Angeles, with 39, and Miami, with 24. All of the 10 most common locations for incidents were cities with populations of over 200,000.

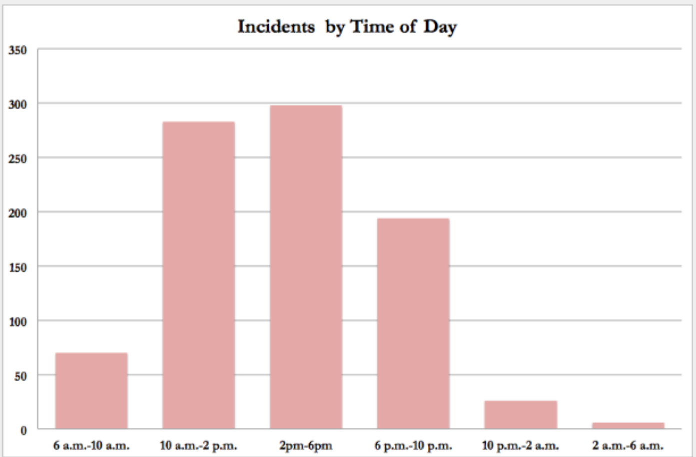


Figure II.9 Sightings and Close Encounters time of day

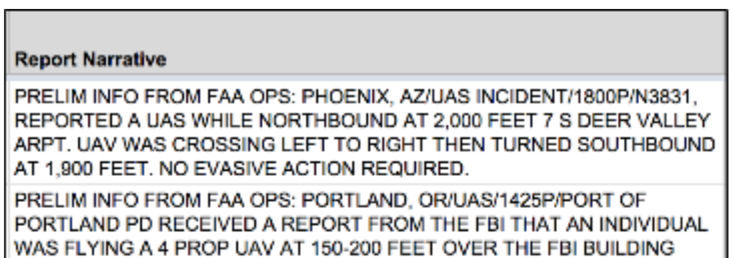
LOCATIONS WITH MOST INCIDENTS	
New York/Newark	86
Los Angeles	39
Miami	24
Chicago	20
Boston	20
San Jose	19
Washington	19
Atlanta	17
Seattle	17
San Diego	14
Orlando	13
Houston	12
Portland	12
Denver	10
Dallas/Fort Worth	11

Figure II.10 Locations with greatest number of Sightings and Close Encounters

III. Methodology

Given that our dataset consists of narrative reports of incidents, and given some of the differences of opinion discussed in Chapter I regarding how to interpret these reports, our methodology has been focused on identifying those reports, data points, and conclusions that can be presented and analyzed with a reasonable degree of confidence. The FAA has released over 1,000 reports of incidents, but these include duplicated reports, as well as reports of drones being flown in such a way that they do not interfere in any way with manned aircraft. We considered each report on a case-by-case basis and, whenever possible, drew from other sources such as the NASA ASRS and SAFECOM databases, as well as media reports. These supplementary materials often contained additional information, such as a personal statement by the reporting officer, that was not available in the FAA data. We have filtered the dataset to include only incidents where a drone is interfering with manned aircraft traffic in the national airspace. The result is a list of 921 incidents.

These incident reports generally provide data, time, location, state, and a narrative of the incident. We carefully reviewed each narrative to extract the following key data points: distance from incident location to the nearest airport, altitude of the incident, drone-to-aircraft proximity, and unmanned aircraft type. For incidents that we classified as Close Encounters, we extracted information about the manned aircraft involved in the incident. Not all incident reports included all of the data points; for example, 256 reports did not indicate the distance to an airport (665 did record a distance). All analysis of particular data points, such as airport distance, is therefore limited to only reports that include that information.



Report Narrative
PRELIM INFO FROM FAA OPS: PHOENIX, AZ/UAS INCIDENT/1800P/N3831, REPORTED A UAS WHILE NORTHBOUND AT 2,000 FEET 7 S DEER VALLEY ARPT. UAV WAS CROSSING LEFT TO RIGHT THEN TURNED SOUTHBOUND AT 1,900 FEET. NO EVASIVE ACTION REQUIRED.
PRELIM INFO FROM FAA OPS: PORTLAND, OR/UAS/1425P/PORT OF PORTLAND PD RECEIVED A REPORT FROM THE FBI THAT AN INDIVIDUAL WAS FLYING A 4 PROP UAV AT 150-200 FEET OVER THE FBI BUILDING

Figure III.1 Typical incident report narratives.

One of the challenging data points to extract from the reports was the type of drone involved in the incidents. Many of the incident reports identified the drone type in some way, but the level of detail in descriptions varies widely and the exact model of drone is absent from the majority of the data. Instead, the reporting party usually identified the drone by the color, size, and shape of the unmanned aircraft. For example, the pilot might report seeing a drone that was white and sported flashing lights and was 3 feet long. In some cases, the pilot likened the unidentified aircraft to some recognizable shape like a "crab" or a "dishwasher."

We classified drones involved in incidents based on the reported attributes such as the number of propellers, how it was flying, and the type of activity that the drone was engaged in at the time. For example, if the pilot reports a drone with multiple propellers and a 1-foot diameter hovering above them, the drone is clearly a multirotor. Whereas if the drone is described as having wings and a length of 3 to 4 feet, it is more than likely that it is a fixed-wing unmanned aircraft. A small number of other reports describe the unmanned aircraft as a helicopter-type drone or an aircraft with a single propeller, which we classified as helo-type drones.

A significant task in our preparation of the data was grading the incidents based on severity. As we set out to classify incidents into two categories—Sightings and Close Encounters—we considered various factors in developing a set of criteria that we could use to measure their severity. First, we considered the FAA's definition of a NMAC. According to U.S. Department of Transportation Order 8020.11,[14] the FAA considers there to be a "severe" or "potential" risk of a NMAC occurring when there is 500 feet or less of separation between two aircraft or in the event that a crewmember reports that there was a risk of collision with another aircraft.

The FAA's NMAC guidance provides a baseline for assessing the level of risk in the reports, but the FAA's NMAC criteria were developed for manned vs. manned conflicts, and we did not feel that it was necessarily appropriate, without a full official study on manned vs. unmanned conflicts, to use these same criteria as a strict rule for distinguishing incidents involving drones from one another. The NMAC guidance assumes that the pilots of the two aircraft have enough training to recognize when an aircraft comes too close to another, and will know how to resolve the situation (all pilots are required to be capable of detect-and-avoid).[15] The operators of drones do not necessarily have that level of understanding or experience. Moreover, even with aids like first-person view and an additional person to spot oncoming hazards, drone operators may have a reduced ability to see and avoid other traffic, particularly at elevated altitudes and speeds. Finally, unlike manned aircraft, drones are not equipped with electronic equipment such as transponders that identify them to air traffic controllers and to other aircraft in the area.

The FAA has not released codified criteria for NMAC specifically involving a drone and a manned aircraft. As such, our criteria for defining an incident as either a Close Encounter or a Sighting include a variety of factors in addition to the 500-foot aircraft-to-aircraft proximity threshold. The U.K.'s Airprox Board, which determines the cause and risk of near-miss incidents, conducted several investigations into incidents involving drones over the past year. In publicly available summaries of the Board's discussions, the members analyze the situation and take into account any extenuating factors that might apply to drones. For example, in one such incident, the crew of a Boeing 737

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[14]U.S. Department of Transportation, Federal Aviation Administration, Aircraft Accident and Incident Notification, Investigation and Reporting, Misc. Doc. (2011). Accessed December 6, 2015. https://www.faa.gov/documentLibrary/media/Order/8020.11C%20with%20Chg%201.pdf.

[15]Federal Aviation Administration. *Overview — Title 14 of the Code of Federal Regulations (14 CFR).* Accessed December 6, 2015. https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_handbook/media/FAA-8083-30_Ch12.pdf.

reported seeing a black and white drone at 1,800 feet.[16] The Board members determined that although there was no measurable proximity between the two aircraft, "after some debate, they decided that for the drone to have been identified specifically as a black and white 4-rotor drone this indicated that it was probably closer than the pilots' estimate of 300 meters." In these incidents, Board members considered the implications of the drone's involvement and the conditions at the time.

The Airprox Board reports reaffirm the need to make a holistic evaluation of each incident and to consider environmental factors that may not be explicitly stated in the pilot accounts. Crucially, the reports reflect the at times unique challenges presented by drones to manned flight and the difficulty in applying the same standards to drone operators as to pilots. In our analysis, we looked for a preponderance of evidence in the data before reaching a decision as to the level of risk posed by the drone to the aircraft. The FAA's 500-feet rule remained an important baseline among a number of considerations, but in the absence of proximity data, we were able to turn to other factors, as the Airprox Board does, to make a high-confidence decision about the nature of the incident.

[16] Civil Aviation Authority, Airprox Board. *Airprox Report*. Report no. 2015109. UK Airprox Board, 2015. Accessed December 6, 2015. http://www.airproxboard.org.uk/docs/423/2015109.pdf.

IV. Potential Consequences of a Collision

What would happen if a drone were to collide with a manned aircraft? Since we have so far only seen a couple of minor, unconfirmed midair collisions, and since no live tests have been conducted to show the results of different kinds of collisions under various conditions, there is currently little consensus within the aerospace and aviation community as to the answers to this question. While it is possible to make predictions about the possible effects of a major collision, the actual effects will not be fully known until live testing has been conducted. The effects of bird strikes on aircraft have been well-documented and studied (there were roughly 11,000 bird strikes in 2013 in the U.S. alone[17]), but bird strike data only provides a limited amount of guidance when it comes to determining the possible consequences of a drone strike.

On April 27, 2015, a pilot operating a single engine propeller-driven Cessna 206 reported "hearing a loud thump and a jolt to the aircraft climbing out of 4,500ft…

> "Pilot inspected aircraft after landing at CNO. Aircraft had sustained two gouges to the lower portion of the nose cowl about 3 inches long and deep enough to take off the first layer of fiberglass. Evidence of impact with the inside of two of the three props was evident. There was no blood found anywhere on the aircraft as would have been expected with a bird strike."

The collision resulted in a lesion in the aircraft's skin that, while significant, was not big enough to seriously destabilize the aircraft. A drone might not necessarily hit the wing or the propellers, however. With sufficient speed, bird strikes have been known to penetrate the cockpit. It is entirely possible, then, that a drone could also break through into a cockpit, potentially causing serious harm to the pilots or other occupants.

Per FAA Federal Aviation Regulations 33.76 and 33.77, engine manufacturers are required to test their engines' ability to ingest birds, water, and ice without sustaining catastrophic damage.[18] However, companies have not yet been required to conduct similar tests with drones. According to a story published by NBC News in August 2015, "CFM, GE, Rolls Royce, and Pratt & Whitney, which combined account for more than 80 percent of the engines used by the world's commercial planes, all confirmed they had not conducted such tests because the FAA has not yet mandated such

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[17] *Wildlife Strikes to Civil Aircraft in the United States 1990–2013*. Report no. 20. Washington, DC: Federal Aviation Administration, 2014. Accessed December 6, 2015. http://wildlife.faa.gov/downloads/Wildlife-Strike-Report-1990-2013-USDA-FAA.pdf.

[18] Federal Aviation Administration. *Title 14 of the Code of Federal Regulations (14 CFR), 33.76-33.77*. Accessed December 6, 2015. http://www.ecfr.gov/cgi-bin/text-idx?node=pt14.1.33&rgn=div5.

testing."[19] While the FAA has not yet announced officially when it will begin to require engine manufacturers to conduct drone ingestion tests, it has unofficially acknowledged that it is working on the issue. According to the text of the Department of Transportation's Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC) Recommendations Final Report, the FAA is currently working "in this area."[20]

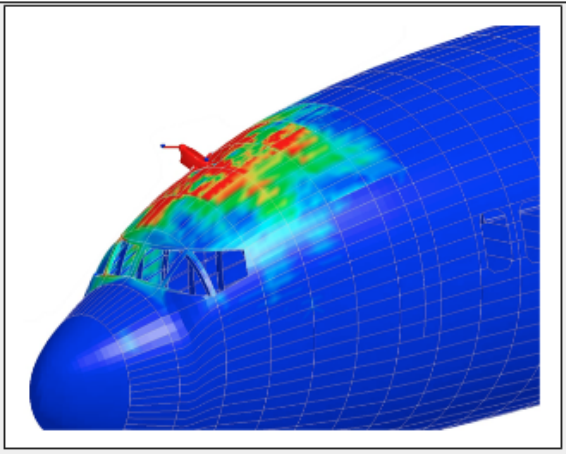

Figure IV.1 A simulation of a drone impact on an aircraft's fuselage

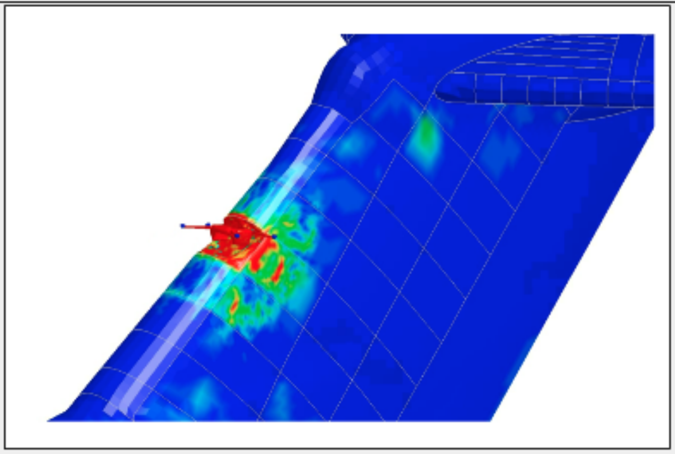

Figure IV.2 A simulation of a collision affecting the tail section of a manned aircraft

Images Courtesy of the Virginia Tech CRASH Lab

In the meantime, research is being conducted to predict the consequences of a drone strike. A team of engineers at the Crashworthiness for Aerospace Structures and Hybrids (CRASH) Lab at Virginia Tech[21] has delved into this question in an effort to understand how the consequences of a drone strike might be different depending on where the strike took place on the aircraft. Using the history of bird strikes as an indicator of where drone strikes might occur, the CRASH Lab proceeded to develop complex computer simulations of strikes between manned aircraft and drones. Here is a brief summary of CRASH Lab findings:

> "The potentially at risk systems of an airplane are the radome, front exterior of the flight deck or cockpit, wing and empennage leading edges and their related lifting and control surfaces including slats, Krueger flaps, and vertical and horizontal stabilizer and, finally, the propulsion system. If an airplane with an aft engine is subjected to impact with a drone over its wing or cockpit, there will be a higher chance of the resulting debris being ingested into the engine after the initial contact.

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[19]Winter, Tom, and Jay Blackman. "Jet Engines Have Not Been Tested Against Drone Strikes." *NBC News*, August 13, 2015, Tech News. Accessed December 6, 2015. http://www.nbcnews.com/tech/tech-news/engine-makers-havent-tested-drones-n408711.

[20]Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC). *Task Force Recommendations Final Report.* 2015. Accessed December 6, 2015. https://www.faa.gov/uas/publications/media/RTFARCFinalReport_11-21-15.pdf.

[21] Javid Bayandor, PhD, Director; Walter, O'Brien, PhD; Yangkun Song; and Kevin Schroeder.

> "Based on mass and size of hobbyist's drones, they can exert different degrees of damage on impact to an airplane. Professional multi-copter drones that are commercially available (4-5 kilograms) can cause irreversible damage on the primary structures of the airplane (including the flight deck windshield pillars), or potential catastrophic failure on non-primary (secondary) structural components (such as control surfaces, radome, flaps, slats, etc.). Large and medium sized hobby drones (1-3 kilograms) can potentially cause critical damage. The impulse at impact for this type of drones can be large enough to damage non-primary structures."

The team conducted simulations of a small unmanned aircraft being ingested into a turbofan engine. They found that a 3-foot diameter drone, if ingested into a 9-foot diameter turbofan engine, could potentially cause up to three of the engine blades to fail, and might result in loose debris moving around the engine chamber at speeds of up to 700 miles per hours. These factors, the team concludes, could cause engine failure.

Helicopters, which accounted for just over 10 percent of Close Encounters in our dataset, are also at risk of bird strikes, and are therefore also probably vulnerable in a collision with an unmanned aircraft. According to the U.S. Department of Agriculture, bird strikes against helicopters have resulted in 61 injuries and 11 deaths in the U.S. since 1990.[22] In Louisiana in 2009, a strike between a private helicopter and a red-tailed hawk caused the aircraft to crash, resulting in eight fatalities.[23] The CRASH Lab team is preparing simulations to study the potential effects of a collision between a helicopter and a drone.

In the accompanying figures, which were produced by CRASH Lab through simulations of collisions between a manned aircraft and a drone, cold colors (blue and green) represent areas with minimal structural stress, while hot colors (red and orange) represent significant stress, including stresses that are greater than the strength of the affected components, which could trigger structural failures.

According to the CRASH Lab team, "Once an engine has ingested a drone, it will suffer from a minimum of operational stability issues, to a maximum of thrust loss due to catastrophic failure."

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[22]Gail Keirn, "Helicopters and Bird Strikes; Results from First Analysis Available Online," *USDA Blog*, entry posted June 6, 2013, accessed December 6, 2015. http://blogs.usda.gov/2013/06/06/helicopters-and-bird-strikes-results-from-first-analysis-available-online/.

[23]USDA National Wildlife Research Center. *Wildlife strikes to civil helicopters in the US, 1990–2011*. By Brian E. Washburn, Paul Cisar, and Travis L. DeVault. Elsevier, 2013. Accessed December 6, 2015. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2245&context=icwdm_usdanwrc.

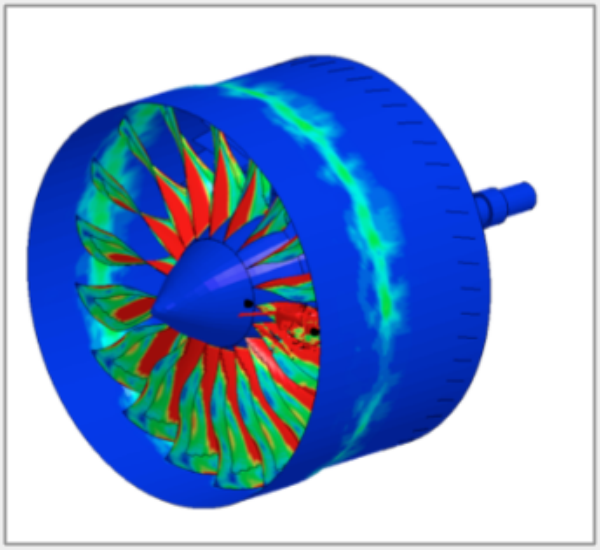

Figure IV.3 Engine damage 1.7 milliseconds following impact. The drone is mostly ingested, and high levels of stress are exerted on the engine blades.

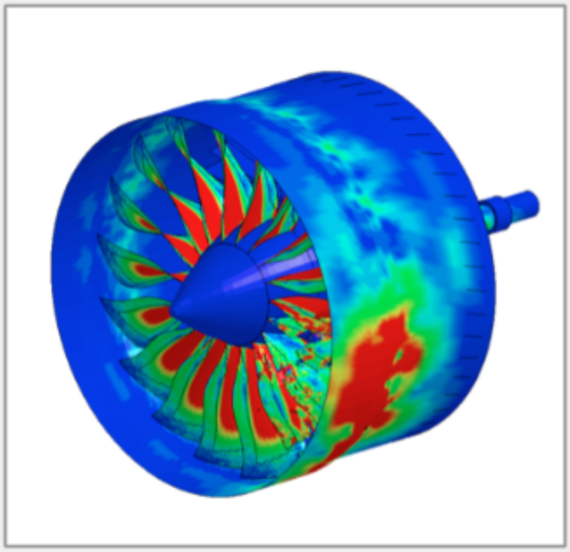

Figure IV.4 Engine damage 6 milliseconds following impact. Failure of the engine blades and moving debris would exert stress on the engine casing.

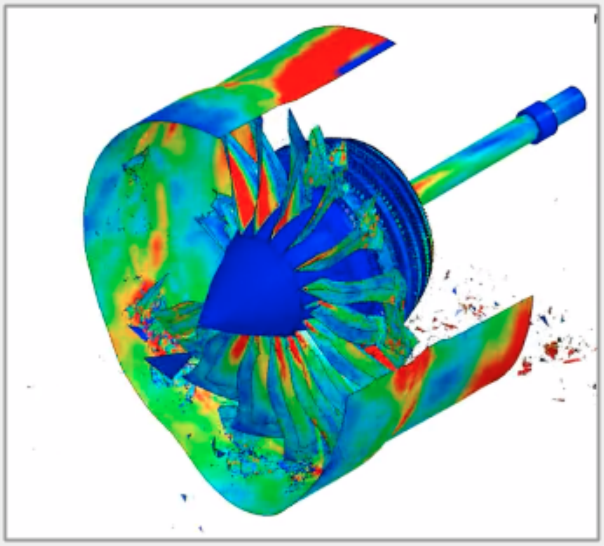

Figure IV.5 Engine damage 17 milliseconds following impact. The drone has been completely ingested and stresses are visible on various engine components.

Figure IV.6 Blade damage following drone ingestion. After the drone cleared the fan stage of the engine in the simulation, three engine blades had failed.

Images Courtesy of the Virginia Tech CRASH Lab

V. Solutions

There are a variety of parallel efforts underway to develop solutions that might reduce or prevent future incidents involving drones in the national airspace.

Geo-fencing: This is a system that uses software to limit where unmanned aircraft can fly. DJI, a company that produces the popular range of Phantom commercial multirotor drones, has installed geo-fencing software in its unmanned aircraft that restricts users' ability to fly within five miles of an airport or within certain restricted airspaces such as Washington, D.C.[24] The geo-fenced locations are drawn from an app called AirMap, which maintains an up-to-date list of restricted airspaces. Meanwhile, 3DR, another popular commercial drone maker, has announced that its Solo multirotor drone will be installed with the AirMap app in order to indicate to the operator whether or not the drone is being operated within restricted airspace.[25] Geo-fencing systems are not currently required by the FAA.

Two Contrasting Views on Geo-fencing

"Geofencing will be an essential technological solution. This will allow manufacturers to govern where their vehicles fly, providing a 'backup' to people who mean well but who don't necessarily read and follow instructions... A small UAS equipped with keep-in geofencing can have an 'operational ceiling' governed by validated software rather than aerodynamics and weight. This will be a big deal for flight safety, as it separates the low-flying multicopters from the higher-flying manned traffic. For small UAS that truly do not need to share high-altitude airspace with larger manned traffic, geofencing will be easier and lower-cost than requiring certified sense-and-avoid on every platform. Primary research challenges in geofencing are related to resilience given potential for anomalies/failures as well as operator equipment tampering." — Ella Atkins, associate professor of aerospace engineering at University of Michigan.

"That may help some people who are clueless, but that's relatively easy to defeat if you don't want to comply with it. So the whole idea of geofencing is pretty bogus. It's useful if you have a cooperative user. But a non-cooperative user who doesn't want to geofence can get around it. You just cut off their flight control system and put on your own. The real solution is not just a technical solution. It's in part having the correct and reasonable UAV rules that makes sense, that are defendable from a public policy standpoint. I also think that having some sort of identification and tracking of the vehicles makes sense, so that when you do have a case of someone inappropriately using one of these UAVs, you have a way to identify who it is. Right now people feel relatively anonymous. They don't feel like they have to take responsibility for their actions in the same way that you would if there was a real tracking system." — R. John Hansman, director of the MIT International Center for Air Transportation

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[24] DJI. "DJI Introduces New Geofencing System for its Drones." News release. November 17, 2015. Accessed December 6, 2015. https://www.dji.com/newsroom/news/dji-fly-safe-system.

[25] "3DR Collaborates with AirMap to Integrate Flight Safety Zone Software into the Solo App." *3DR* (blog). Entry posted November 17, 2015. Accessed December 6, 2015. https://3drobotics.com/3dr-collaborates-with-airmap-to-integrate-flight-safety-zone-software-into-the-solo-app/.

Sense-and-avoid: Sense-and-avoid systems allows unmanned aircraft to autonomously detect a potential collision with another aircraft and take evasive action, just as a human pilot would. Various groups are working to develop reliable sense-and-avoid systems that can match the detect-and-avoid capability of a human, and the FAA is working to develop common standards for the technology.[26] Much of the research on sense-and-avoid systems is focused on larger unmanned aircraft that are capable of carrying heavy transponder systems. The U.S. military is also working on various sense-and-avoid systems for unmanned aircraft.[27] Some systems for small unmanned aircraft are under development, though they may not be designed to operate at high altitudes and high speeds.

Traffic Management: One way of keeping drones and manned aircraft separate is to implement an air traffic control system similar to the one currently in use for manned aircraft. NASA's Unmanned Aircraft Systems Traffic Management initiative is looking to build a management system that would provide drone operators with "airspace design, corridors, dynamic geo-fencing, severe weather and wind avoidance, congestion management, terrain avoidance, route planning and re-routing, separation management, sequencing and spacing, and contingency management."[28] The system, which involves a combination of technologies including a traffic management platform developed by U.S. drone maker PrecisionHawk, 4G cellular networks, and satellite imagery, completed its first round of tests in October 2015.[29] NASA plans to conduct further testing in three stages over the next three or four years, at which point the system will be transferred to the FAA for further testing and certification.

Registration: In November 2015, a task force convened by the Department of Transportation submitted a set of recommendations for rules that would require drone users to register their aircraft. According to the recommendations, users would register drones weighing more than 250 grams through an online registration system, and would be required to paste their aircraft's registration number on the airframe. This system would allow law enforcement and the FAA to

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26 Hottman, S. B., K. R. Hansen, and M. Berry. *Literature Review on Detect, Sense, and Avoid Technology for Unmanned Aircraft Systems*. Washington, DC: Federal Aviation Administration, 2009. Accessed December 6, 2015. http://www.tc.faa.gov/its/worldpac/techrpt/ar0841.pdf.

27 Insinna, Valerie. "Military, Industry Racing to Create Sense-and-Avoid Systems." *National Defense*, May 2014. Accessed December 6, 2015. http://www.nationaldefensemagazine.org/archive/2014/may/pages/military,industryracingtocreatesense-and-avoidsystems.aspx.

28 "NASA UTM: Homepage," National Aeronautics and Space Administration, accessed December 6, 2015, http://utm.arc.nasa.gov/index.shtml.

29 PrecisionHawk. "Industry leaders in cellular, aircraft surveillance, satellite imagery and drones bring together the best technology solutions to enhance safety as airspace congestion increases." News release. October 26, 2015. Accessed December 6, 2015. http://www.prnewswire.com/news-releases/precisionhawk-verizon-harris-and-digitalglobe-jointly-demonstrate-technology-for-safe-drone-operations-300165900.html.

track unmanned aircraft that are involved in incidents back to the owner.[30] However, since many of the incidents in our database involve drones operating at relatively large distances from manned aircraft, it may not always be possible for the reporting party to identify the registration number on the drone.

Education: There is a high level of consensus among experts with whom we have consulted that lack of awareness of airspace rules and guidelines on the part of drone operators is a major contributing factor to incidents involving drones in the national airspace. Therefore, educational campaigns have been identified as a potential means of reducing the rate of such incidents. The biggest and most concerted of these campaigns is the Know Before You Fly initiative, which was launched in December 2014 as a collaboration between the Association for Unmanned Vehicle Systems International—the largest trade association for unmanned technology manufacturers—the Academy of Model Aeronautics, and the FAA. The campaign, which has been joined by 32 supporting organizations such as Amazon, the Air Line Pilots Association, and DJI, provides information about guidelines and airspace rules for drone operators, and produces educational awareness campaigns in a variety of media.

[30]Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC). *Task Force Recommendations Final Report*. 2015. Accessed December 6, 2015. https://www.faa.gov/uas/publications/media/RTFARCFinalReport_11-21-15.pdf.

Conclusion

The growing popularity of drones among consumer and commercial users presents a unique challenge to regulators and policymakers. While the reporting in the incidents collected in our database may at times be inconsistent, these accounts are the best and most detailed source of information on Close Encounters and Sightings involving drones and manned aircraft in the National Airspace System. The data offers a way forward in understanding the areas of greatest risk and how an accident might occur. It also highlights avenues for making the airspace safer for everyone.

> "If we're going to develop some common sense policy out of this committee, we need to have good data Rep. Ann Kirkpatrick said at the October 7, 2015 House hearing on aviation safety.

Preventing the kinds of incidents that could potentially pose a threat to public safety will likely involve a combination of approaches, and will most definitely depend upon the collaboration of a multitude of stakeholders. Our role with this report has been to furnish those stakeholders, as well as the public at large, with a detailed analysis of these incidents, in the hope that the information might be useful in the development of effective policies and technological solutions.