Integrating Drones into the US Air Traffic Control System

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Abstract

The technology already exists to build drones that are able to electronically see and avoid other aircraft. Drones of all sizes can be integrated into the air traffic control system by using this technology and maintaining the current requirement that drones yield the right-of-way to other aircraft. This technology is already used in piloted aircraft, and examining how drones can be integrated into the air traffic control system suggests ways that the system can be improved for piloted aircraft as well. The current system is a centralized system in which aircraft follow the instructions given by air traffic controllers. Current technology would allow a redesign so that both piloted and unmanned aircraft could fly when and where they want. Such a system would resolve potential conflicts in a decentralized manner as they arise, without the need for centralized control of air traffic.

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Integrating Drones into the US Air Traffic Control System

Randall G. Holcombe

One of the challenges that comes with the increasing use of unmanned aerial vehicles—UAVs, or drones—is integrating them into the air traffic control (ATC) system so that they do not conflict with other aircraft. On June 21, 2016, the Federal Aviation Administration (FAA) issued regulations applicable to unmanned aircraft systems weighing less than 55 pounds.[1] The rules fall short of integrating unmanned aircraft into the ATC system because they limit the weight of drones to less than 55 pounds, they limit the altitude for drones to 400 feet or less, and—more significantly—they require drone operators to maintain visual contact with their drones. The rules will surely be modified in the future. One provision, if retained, can lay the foundation for integrating drones of all types into the ATC system: drones "must yield right of way to other aircraft." A discussion of how this work of integrating drones into the ATC system can be done points to a much broader conclusion: the entire air traffic control system can be modified to make it work better for all aircraft.

The current focus of both rules for drones and popular discussion of drones is on smaller drones. For example, Amazon has announced its intention to use a fleet of package-delivery drones, filmmakers want to use them as camera platforms, and farmers want to use them to monitor their land. Moreover, drones can replace manned aircraft for pipeline patrol, and they are already being used in law enforcement and border patrol. Ambulance drones can

[1] The 624-page document, "Operation and Certification of Small Unmanned Aircraft Systems," is available at https://www.federalregister.gov/articles/2016/06/28/2016-15079/operation-and-certification-of-small-unmanned-aircraft-systems.

offer quick-response emergency medical care.[2] In addition, a growing hobbyist community is flying drones. The future is also bright for larger drones. FedEx uses large cargo jets with autopilots that currently can fly the aircraft from takeoff to touchdown. With all the discussion of self-driving cars, aircraft already have the technology to fly unmanned. Between the small Amazon package-delivery drones and the large package-delivery aircraft of FedEx are remotely piloted military drones, already in operation. It is easy to imagine intermediate-sized drones delivering passengers and cargo.

Whether these uses actually materialize depends partly on the rules. The rules should be designed to be forward looking to accommodate not just Amazon's package-delivery drones, but also ambulance drones that fly patients to hospitals, taxi drones, and so on—drones for all uses. If the one current rule that drones "must yield right of way to other aircraft" is maintained, current technology would allow any type of drone, for any type of use, to be integrated into the ATC system. This study explains how that integration can be achieved.

The Current Rules of Air Traffic Control

Conflict avoidance in aviation is currently managed under two different sets of rules. Aircraft can choose to fly under visual flight rules (VFR), which allow pilots to fly where they want and place the responsibility on them to see and avoid other aircraft. Alternatively, they can choose to fly under instrument flight rules (IFR), which require them to file a flight plan and follow a route that is approved by ATC.[3] Decision making under VFR flight is decentralized: pilots make their

[2] See Alec Momont, "Drones for Good," web project, accessed July 25, 2016, http://www.alecmomont.com/projects/dronesforgood/.

[3] These regulations are in Title 14, Chapter I, Aeronautics and Space, of the Code of Federal Regulations. Flight rules are in Part 91, Subpart B. Visual Flight Rules are found in Part 91.151–161 and Instrument Flight Rules are found in Part 91.167–193.

own decisions about where to fly and are responsible for avoiding conflicts with other aircraft. IFR flight is organized through centralized decision making, in which pilots follow flight plans approved by ATC and follow ATC instructions to avoid conflicts. The current rules for drones are similar to VFR in that drone operators are responsible for seeing and avoiding other aircraft.

Flight under VFR is, ideally, how all flight should take place. Pilots fly where they want, when they want; when conflicts arise, the pilots themselves maneuver to avoid them. Decision making is decentralized—the pilots make the decisions—rather than centralized through ATC. A big limitation of VFR flight is that pilots must see and avoid other aircraft, which means they must fly clear of clouds. IFR is required when flying in clouds because pilots cannot see each other. Under IFR, ground-based air traffic controllers track each flight and give instructions so that routes do not conflict.

IFR have seen little change since the 1940s, but the technology for conflict avoidance has advanced substantially. In the 1940s, when there was no radar coverage for en route flight, IFR aircraft would fly from one ground-based radio navigation station to the next, reporting their positions to ATC by radio. ATC would keep track of those locations and assign routes so that aircraft did not conflict. Today, aircraft are equipped with transponders that broadcast an identifying code and altitude to ATC.[4] An aircraft shows up on radar along with a unique identifier, its altitude, and its airspeed.

Airliners and other larger aircraft are equipped with a traffic collision avoidance system (TCAS), which enables such aircraft to pick up the transponder broadcasts of other aircraft. TCAS enables pilots of airliners to "see" other nearby aircraft on a cockpit display even when they cannot see those other aircraft visually. In addition to spotting potential

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[4] Regulations for equipment are found in Title 14, Chapter I, Aeronautics and Space, of the *Code of Federal Regulations*, Subpart C of Part 91.

conflicting traffic, TCAS gives traffic resolution advisories that direct pilots to maneuver their aircraft to avoid other aircraft—for example, by climbing or descending. Commercial passenger aircraft with more than 30 passenger seats have been required to be equipped with TCAS since 1993.

Beginning in 2020, all aircraft that are now required to have transponders also will be required to be equipped with an automatic dependent surveillance–broadcast transponder (ADS-B). ADS-B uses GPS signals to determine an aircraft's location and broadcasts that location to ATC and to other nearby ADS-B aircraft. Despite the advances in technology, IFR aircraft separation works today the same way that it did in the 1940s. Air traffic controllers keep track of the locations of aircraft and assign them routes so that they will not conflict. In the 1940s, aircraft flying in clouds could not see each other, but today, aircraft with TCAS and ADS-B can see each other electronically and have the ability to avoid conflicts without ATC direction. Today's technology allows aircraft to see each other electronically, regardless of whether aircraft can be seen visually. Current technology would allow all aircraft to see and avoid each other in any weather condition, so the freedom and convenience of VFR flight could be applied to all flights, whether the aircraft are manned or unmanned. The technology is there, but the system has not been modified to take advantage of it.

Free Flight

Technological advances hold the promise of allowing aircraft to determine their own flight paths independent of centralized direction through ATC. In fact, this idea of "free flight" has been around since at least the early 1970s. An article in *Wired* magazine from 1996 briefly describes the current ATC system along with the free flight alternative where pilots use satellite navigation, which the article envisions will be in place "15 years from now."[5] More than 20 years after that article was written, ATC has not changed at all.

One reason that this article might not have appeared overly optimistic when *Wired* published it in 1996 was that a year earlier the FAA had created a task force to implement free flight. The task force report had proposed a plan to be implemented in three phases.[6] Phase I was completed in 2002, but unfortunately, the other phases have yet to be started. Free flight remains far off.

One way to administer free flight would be to have controllers monitor flights and give directions to avoid conflicts. Flights are tracked by radar, so controllers can see potential conflicts before they arise. That is done now under IFR, although IFR flights follow a predetermined flight plan, whereas under free flight, aircraft would not be constrained by a flight plan. Another alternative would be to let pilots use TCAS and ADS-B to avoid conflicts on their own. Decision making would be decentralized at the aircraft level rather than centralized under ATC.

In the yet-to-be-designed system of free flight, communications to ensure traffic separation might take place via aircraft-to-aircraft messages, through messages relayed from aircraft to ATC and then back to other aircraft, or through a mixed system that used both messages between aircraft and messages relayed through ATC from the ground. Free flight would work most effectively if it were based on aircraft-to-aircraft communications, with decisions on route changes made either by the pilots or automatically by drones. This approach would not rule out a back-up role played by ATC, but decision making would be more effective if individuals made their own plans within a system of rules rather than having to submit their

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[5] Jacques Leslie, "The Solution to the Antiquated Air Traffic Control System? Make Pilots Their Own Air Traffic Controllers!," *Wired* 4, no. 4, April 1996.

[6] Radio Technical Commission for Aeronautics (RTCA), *Final Report of the RTCA Task Force 3: Free Flight Implementation* (Washington, DC: RTCA, October 26, 1995).

plans to a higher authority for approval. Under free flight, IFR aircraft would operate essentially as VFR aircraft do, flying when and where they want and resolving conflicts with other aircraft as their flights progress. With current technology, aircraft have the ability to electronically see and avoid each other without ATC oversight.

Rules for Large Drones

The current FAA rules cover only small remotely piloted drones (under 55 pounds), but it is easy to envision how larger remotely piloted or autonomous aircraft could fit into the current ATC system. Imagine, for example, FedEx package-delivery jets remotely piloted by individuals on the ground. Under IFR, such aircraft would follow ATC instructions and use voice communications with controllers just as if the pilots were in the aircraft. They could electronically see other aircraft using TCAS and ADS-B. The technology for such a scenario is already available. Aircraft might also use cameras to visually identify conflicting traffic, but VFR aircraft should also be able to see and avoid large drones.

Now consider the possibility of large autonomous drones, programmed to fly without human oversight. Under current IFR, pilots communicate with ATC via radio, but an autonomous drone would have no pilot to talk. One could imagine voice recognition software similar to Apple's Siri that would recognize and respond to voice commands. Although such software may sound like science fiction, Siri would have sounded like science fiction only a few years ago. ATC voice communications use a very limited and specific vocabulary, and aircraft have a limited number of operations that follow ATC instructions (change altitude, turn, adjust speed, alter flight plan), so it should be easier to design this type of artificial voice communication than to design a system with a more open-ended vocabulary like that of Siri.

Another option would work even better. Under the current regulation that drones must yield the right-of-way to other aircraft, drones could be allowed to engage in free flight, as described in the previous section. They could fly autonomously when and where they are programmed, subject to the condition that they always yield the right-of-way to other aircraft. They could use TCAS and ADS-B to identify other aircraft and always give way. The rule of thumb under VFR is that when two aircraft are approaching each other, both turn to the right, thereby avoiding a conflict. Drones could be programmed this way so that two drones, or a drone and a piloted aircraft, would avoid a collision. The decades-old vision of free flight could be applied to large drones, thus allowing them more direct routings and permitting them to resolve their own conflicts.

The technology already exists to allow free flight not only for drones but for all aircraft. Thinking about the way drones can be integrated into the ATC system naturally points toward modifications of the rules that would allow all aircraft to fly whatever routes they want without needing ATC approval. Under that scenario, aircraft would resolve their own conflicts through decentralized decision making, using TCAS and ADS-B to electronically see and avoid other aircraft.

Rules for Small Drones

Current rules for small drones require that they remain within 400 feet of the ground, or if they are flying near structures, to stay within 400 feet of the structure. Current rules for aircraft require that they fly no closer to any vehicle, structure, or person than 500 feet, except when taking off or landing. Because drones are not allowed to operate in the vicinity of airports, the current rules should prevent most conflicts. An example of a possible conflict under current rules would be a medevac helicopter landing on a highway to fly accident victims to a hospital. What could keep an autonomous Amazon package-delivery drone from crashing into that helicopter?

Current rules also require a human operator who maintains visual contact with the drone and is required to yield the right-of-way to other aircraft. So the helicopter–drone conflict in the previous paragraph is covered under current rules. But if Amazon's package-delivery drones are to become a reality, they must be able to fly beyond the visual contact of the operator, and ultimately Amazon would want them to fly programmed routes autonomously, without a human operator. To do so, drones would have to be able to avoid each other, manned aircraft, and ground obstructions such as temporary construction cranes.

One possibility is to require drones operating outside the line of sight of an operator or operating autonomously to be equipped with ADS-B. As long as the 400-foot altitude restriction remains in place, drones will already be separated from most manned aircraft, and manned aircraft operating below 400 feet, such as the medevac helicopter, could be required to be equipped with ADS-B. Drones would electronically see both manned aircraft and each other. Cameras could be used to avoid obstructions on the ground, much as they are used in self-driving cars. The technology already exists. Drones flying below 400 feet and equipped with ADS-B could follow routes of their choosing and resolve conflicts themselves as they arise.

ADS-B systems currently cost about $8,000 and weigh four pounds or more, so small drones using such a system would be costly and would suffer a weight penalty. However, there are alternatives. In an urban area, drones might have a separate system using the cellular network to report positions and avoid conflicts. The drone network could have a ground-based ADS-B receiver to alert drones of nearby aircraft, so each drone would not have to have its own ADS-B equipment. That is just one possibility. The larger point is that technology already exists to allow drones of any size to be integrated into the current ATC system.

Free Flight for All?

The technology that would allow drones to avoid conflicts with other aircraft is currently available for all aircraft. Hence, speculating that drones could use it to fly where they want as long as they avoid other aircraft implies that all aircraft could be allowed to do so. Currently, VFR aircraft have such freedom, with the stipulation that they visually see and avoid other aircraft. They must fly clear of clouds to do so, but because ADS-B allows aircraft to electronically see each other regardless of the weather, free flight would just be a matter of extending the current rules to allow VFR flight in any weather conditions for ADS-B aircraft. A new category of flight rules—free flight rules, or FFR— could be established. Under FFR, properly equipped aircraft flown by pilots with appropriate training could determine their own routes independent of ATC oversight. FFR would stipulate that aircraft see and avoid other aircraft, whether visually or electronically, much as VFR do now, but not subject to visibility constraints. Aircraft would have the option of flying under VFR, IFR, or FFR. Many aircraft now flying under IFR would choose FFR because they could fly direct to their destinations, choosing their own routes and altitudes rather than following an ATC flight plan subject to reroutings.

One advantage of free flight is that it would increase the capacity of the air traffic control system. A decentralized FFR system, like the current VFR system, would prevent conflicts in the air similar to the way that the highway system prevents conflicts on roads. People can get in their vehicles at any time and drive where they want without telling anyone of their plans and without any central traffic coordinator telling them where to drive and how to avoid other traffic. There are rules of the road such as stop signs and traffic lights that indicate who has the right-of-way, and within those rules drivers choose their own routes and see and avoid other traffic as they travel to their destinations.

Imagine a highway system designed and run like the IFR air traffic control system. Drivers would have to file their routes of travel with a central controller ahead of time and follow that plan. Any deviation from the filed plan would have to be approved by the traffic controller, and the traffic controller would be responsible for making sure that vehicles remained separated. Want to change lanes? It has to be filed on your plan, and if not, you need permission from a controller, who must first verify that there is no conflict in that lane, just as IFR aircraft must get permission from ATC before changing altitude. Want to change your destination mid-trip? Again, this deviation would require permission from the highway controller. A controller would not let a vehicle enter a roadway unless he or she could be sure that the vehicle would be separated from traffic that is already there.

Clearly the network of roadways would carry much less traffic than it does now if all trips had to be coordinated through a centralized traffic control system. It would be less convenient for travelers, and it would be more costly to operate. Such a system would also provide much lower capacity if centralized traffic controllers had to verify the absence of conflicts before allowing traffic to enter roadways, change lanes, and so forth.

A second advantage of a decentralized system for air traffic control is that equipment problems that would inevitably arise would affect only the aircraft that have those problems. Because air traffic control relies increasingly on centralized technology, the threat of equipment failures that can shut down the system has grown in recent years. On September 26, 2014, a fire in a Chicago ATC facility completely shut down Chicago's O'Hare and Midway airports, grounding 2,100 flights and preventing IFR flights in Chicago Center's airspace. Normal operations were finally restored on October 13.[7] And on August 15, 2015, a software glitch at the Washington, DC, ATC facility caused the delay or cancellation of 1,000 flights and took several days to resolve.[8] In a decentralized system, if there is a technical problem with equipment on an aircraft, only that aircraft is affected; all other aircraft can continue to fly as planned. In a centralized system, a technical problem with ATC can shut down the whole system and prevent all aircraft from flying. The aforementioned events show that the potential to shut down the system because of technical problems with ATC is real. Indeed, the potential costs of centralization point to the need for decentralization.

Conclusion

Although much of the discussion in this paper has been about air traffic control more generally, the ATC system is well established, and change will surely come slowly. Drones are a more recent phenomenon, and a very real issue concerns how they can be integrated into the system in a way that prevents conflicts with manned aircraft and with each other. The technology to do so already exists, although currently it is relatively expensive and would add a weight penalty to lightweight drones. The current rules mandating flight below 400 feet and requiring drone operators to maintain visual contact with their drones should limit conflict, but those rules also limit the utility of drones. Eventually, drones must be allowed to fly beyond the line of sight of their operators and even operate autonomously, programmed to fly without human operators.

[7] Bradley Sunshine, "Radio Silence: The Incredible Story of the Chicago Air Traffic Fire and the Professionals Who Kept Our Skies Safe," *Flying* 142, no. 8 (2015): 61–67.
[8] Fredrick Kunkle, "FAA, Airlines Still Working to Resume Normal Air Traffic after Major Glitch," *Washington Post*, August 16, 2015.

This study explains how they can do so and also points toward broader modifications in the air traffic control system that can benefit all flights, manned and unmanned.

Current technology would allow an ATC system in which all aircraft flew when and where they wanted. Conflicts between aircraft would be resolved as they arose through a decentralized process in which decisions were made by those controlling the aircraft. This process would be a change from the current centralized process, where aircraft can fly only where they have permission from controllers, and where controllers centrally instruct aircraft where to fly for collision avoidance. The changes recommended here would increase the capacity of the air traffic system, allow more flexibility in flight, allow more direct flights and lower costs, and greatly reduce if not eliminate the need for and the cost of centralized air traffic control. As the FAA considers revising rules to allow drone flight, it should do so in a forward-looking way that would improve air traffic control for everybody.

Appendix: Further Details

This study is designed to be a nontechnical explanation of the air traffic control system and the ways by which drones can be integrated into it. The appendix addresses some questions that were not addressed or were only briefly addressed in the main study.

VFR Flight Rules

With VFR flight, aircraft are not required to communicate with ATC, and they fly where they want, avoiding conflicts on their own. The primary exceptions to this are that (a) when aircraft are within the designated airspace of an airport control tower, they are required to be in radio contact and follow the controller's instructions, and (b) all flight above 18,000 feet is conducted under IFR. Because VFR flight requires aircraft to see and avoid other aircraft, VFR flight must be conducted clear of clouds so that aircraft can actually see each other. But with TCAS and ADS-B, aircraft now can see each other electronically even when they cannot see each other visually. Also, when IFR aircraft are not flying in clouds, current rules require that they see and avoid VFR aircraft, because VFR aircraft could be in the vicinity and not in radio contact with ATC.[9]

In airspace around airports with control towers, VFR flights must follow controller instructions in essentially the same way as IFR flights do. VFR pilots can file flight plans, but they are not required to do so and they do not have to follow those flight plans if they choose to make deviations. Aircraft may fly without a transponder if they are below 10,000 feet and more than 30 miles away from airports with control towers. Thus, aircraft relying on ADS-B for collision avoidance below 10,000 feet will not be able to detect aircraft not equipped with transponders. All VFR aircraft are already required to remain clear of clouds to be able to see

[9] Note, however, that ATC does have radar and will typically contact IFR aircraft to alert them of nearby VFR aircraft. Also, airliners should see VFR aircraft on their TCAS.

other aircraft. Under the FFR suggested in this article, aircraft flying by those rules would have to look for other aircraft when not flying in clouds, just as IFR aircraft do today.

Although VFR allows pilots to fly where and when they want, some rules of thumb are recommended but not required. For aircraft flying toward the east, altitudes of the odd thousands plus 500 feet are recommended. For example, pilots should fly at 5,500 feet or 7,500 feet. West-bound aircraft should fly at the even thousands plus 500 feet, such as 4,500 or 6,500 feet. IFR traffic normally flies at even thousands, such as 5,000 or 6,000 feet. Pilots following these guidelines should not meet head-on traffic.

There are also standard traffic patterns to fly around airports without control towers. Those patterns are recommended but not required. Pilots flying the standard traffic patterns should not encounter conflicts with other aircraft. Also, uncontrolled airports have standard radio frequencies so pilots can announce their positions to other aircraft in the area. Such announcements are recommended but not required. Aircraft operating at uncontrolled airports are not even required to have a radio.

ADS-B

Beginning in 2020, all aircraft now required to have transponders also will be required to be equipped with an ADS-B transponder. ADS-B uses GPS signals to determine the aircraft's location, and it broadcasts the aircraft's location to ATC and to other nearby ADS-B aircraft. The 2020 mandate requires aircraft to be equipped with ADS-B Out, which broadcasts the aircraft's location, but not ADS-B In, which receives ADS-B broadcasts. ADS-B does not replace the transponder requirement, so aircraft will still have to be equipped with transponders. The FFR suggested earlier in this article would require both ADS-B In and ADS-B Out.

The current cost of ADS-B In and Out starts at about $8,000, and a transponder—if required—would add about $1,800 to that cost. ADS-B Out alone would cost about $6,000 (and would not supply the information necessary for drones to avoid other aircraft). Technological advances may lower the cost somewhat over time, but this is the minimum cost in 2016 for the technology to avoid conflict. Current units weigh about four pounds or more, and drone operators must consider this additional weight, which could be a significant percentage of the total weight of a small drone.

Weather Avoidance and Loss of Communications

Pilots often ask for deviations from their flight plans to avoid weather hazards—mostly thunderstorms, icing conditions, and turbulence. Remotely piloted drones could handle such deviations the same way that manned aircraft do. Autonomous drones would have to be equipped with a method of making such a request to ATC, which is a minor technological issue that would need to be resolved. Although the technology exists, it is not a part of the current ATC system. With Siri-like technology, the autonomous drone would "see" a weather hazard on radar, and a synthesized voice would request a course deviation. The drone would have to be able to hear the ATC response to the request, however, which could be done just as Siri hears requests or over the ADS-B data link. Indeed, the request itself could be done over ADS-B. As the rules currently stand, a request is made to ATC, ATC responds to the request, and the aircraft acknowledges and acts in accordance with the response.

One advantage of communicating via ADS-B would be that it can reduce congestion on the ATC radio frequency, which can be a problem in busy areas. A disadvantage, however, is that other aircraft would not be able to hear the communications between controllers and drones.

Hearing broadcasts from other aircraft can be helpful for avoiding hazardous weather or for understanding what traffic might lie ahead for an aircraft. Equipping drones with voice communication ability would add to the cost of a drone, just as ADS-B would. This added expense would provide an incentive for drone operators to look for less costly ways of making course deviations and of avoiding other aircraft.

What if communications were lost between ATC and the drone, or between the drone and its remote operator? Current rules for manned aircraft specify that in the event of a communications loss, IFR aircraft continue on their assigned flight plan. Those rules would work for drones. ATC knows that in the event of lost communications, the aircraft cannot respond to ATC, so ATC keeps other aircraft from coming in conflict with aircraft that have lost communications. No changes in the rules would be needed. Under FFR, communication with ATC would not be required.

Drones under Visual Flight Rules

Flying under the current IFR system is incompatible with many envisioned uses of drones because the minimum altitudes for IFR flight are relatively high and because a drone's mission may require it to deviate from a predetermined flight plan. Drones flying pipeline patrol or monitoring farmland would need to be lower than current IFR allow. The minimum altitudes for IFR flight are established to provide sufficient clearance above terrain and obstacles. Drones undertaking surveillance (for law enforcement, as an example) might need to change their flight path at a moment's notice.

Under VFR, flight pilots have the responsibility to see and avoid other aircraft. To consider how this responsibility could be met, start with the easiest case: all aircraft, including all drones, are equipped with ADS-B In and Out. In such a case, drones can "see" other aircraft and take action to avoid them, and similarly, manned aircraft can see drones and can take evasive action. However, the 2020 rules only require aircraft to have ADS-B Out, which means that those with the minimum required equipment would broadcast their locations but would not be able to see other aircraft electronically. With no change in the existing rules, the problem of drones conflicting with manned aircraft could be solved if drones had ADS-B In and Out. The drones could use their electronic capabilities to avoid other aircraft, and manned aircraft would be responsible for seeing and avoiding drones just as they are now when operating VFR.

Two potential problems arise with this solution for drones that are considerably smaller than manned aircraft. The first of these problems is that it will be much more difficult for pilots to see smaller drones. This problem might be addressed by writing the rules such that the drones have the responsibility to avoid other aircraft, just as is the case with radio-controlled aircraft today. If the ADS-B technology were significantly trusted, this approach could keep drones from coming in conflict with manned aircraft even when drones flew beyond where their operators could see them. However, if a drone were flying slowly, it might lack the ability to avoid an aircraft that was rapidly approaching.[10] The second problem is that small drones might bear a considerable penalty in terms of weight and expense from being required to carry ADS-B. Drone operators will surely argue that the missions their drones will fly will keep them away from

[10] Aircraft have a speed limit of 250 knots (288 miles per hour) when flying below 10,000 feet. A drone flying 20 miles per hour might have trouble avoiding an aircraft approaching at that speed because the drone could not get out of the way fast enough. However, the aircraft could easily avoid the drone if both were equipped with ADS-B In and Out. As a practical matter, almost all aircraft flying that fast would be on IFR flight plans, and drones would be unlikely to conflict with their flight paths. The most likely type of conflict would be with military aircraft, which sometimes do fly at high speeds and low altitudes. For example, on July 7, 2015, a military F-16 fighter jet on a training mission collided with a small Cessna 150 over South Carolina. See Tyler Pager, "2 Killed When F-16, Cessna Collide in Midair over S.C.," *USA Today*, July 8, 2015, http://www.usatoday.com/story/news/nation/2015/07/07/f16-crash-south-carolina/29815069/.

manned aircraft without ADS-B, and in many cases this will be true. Amazon's package-delivery drones, for example, are unlikely to conflict with manned aircraft.

The current requirement that drones fly no higher than 400 feet above the ground goes a long way toward mitigating conflicts between drones and manned aircraft. Manned aircraft could then maintain at least a 100-foot separation from drones by flying at 500 feet and above. Aircraft rarely fly lower than this altitude, although helicopters routinely fly below 1,000 feet and may engage in off-airport landings.

Risks of Free Flight

If FFR offers so many advantages over the current system, why has it not already been implemented? That question assumes that government does things the most efficient way. Consider the incentives that government decision makers are faced with. The current system has worked extremely well to avoid collisions among aircraft. It would be difficult to fault FAA decision makers for keeping the current IFR-VFR rule structure, with its excellent safety record, even though it creates congestion and adds to the cost of flying. In contrast, it would be easy to fault those decision makers if they adopted FFR and an accident happened. The accident would not even have to be the result of FFR. Questions would still arise about whether that accident would have occurred under the former system, and those who initiated the changes would be blamed, rightly or not. Incentives in government often lead to conservative rulemaking (in the sense that government officials are often hesitant to change the rules).

Pilot Qualifications for Free Flight

Current rules set different minimum qualifications for pilots flying under IFR versus VFR. Pilots who fly under IFR must earn an instrument rating to add to their pilot licenses, to demonstrate their proficiency in flying an aircraft solely with reference to the aircraft's instruments. This is not an issue. The current instrument rating standards could remain, and one of the FFR could be that pilots without the rating must fly in good visibility, clear of clouds, as is now required.

Congested Airspace

When there are a substantial number of aircraft in an area, aircraft might find themselves in conflict with many other aircraft, making avoidance maneuvers more difficult. Air traffic controllers can prevent such congestion by regulating the number of aircraft in a particular area at any particular time. The ultimate solution to this problem is that free flight will allow an increase in the capacity of airspace, just as what amounts to the same system allows an increase in the capacity of the highway system for motor vehicles. Currently, airspace can accommodate more aircraft if they are flying under the VFR system than if they are flying under IFR. What appears to be a problem is actually a solution to a problem. Consider this issue in more detail to break down the problem into components for when conflicts might arise. In general, there is a lot of room in the sky and relatively few aircraft occupying that space.

Current rules specify that all aircraft flying above 18,000 feet must be on IFR flight plans. So, as a first step toward FFR, one possibility is that the new rules could be applied to all aircraft above 18,000 feet. They could fly where they want, direct to their destinations, using ADS-B to avoid conflicts. Above 18,000 feet there would be no ground-based ATC; it would all be decentralized, and decisions would be made by pilots and drones.

Any pilot will verify that coming into conflict with another aircraft is a very rare event, except around airports, where aircraft would not be flying above 18,000 feet. So it would be easy to extend the arguments made in the previous paragraph to all airspace except for that around airports. The current method of aircraft routing encourages conflicts because flight plans are typically filed to be flown on airways that are defined by radio navigation aids on the ground. This method channels many aircraft onto the same airways, where they are more likely to conflict with other air traffic than if all aircraft flew direct to their destinations. Because conflicts at any altitude are rare events except around airports, the next step toward FFR could be to extend those rules from above 18,000 feet all the way to the ground, leaving the question of how to handle congestion that does occur around airports.

Congested Airports

The most congested airspace is around airports. A problem at very congested airports is that they do not have the runway capacity to accommodate all the aircraft that want to use them. Busy airports handle this problem now with a combination of reservations and "flow control." Aircraft must have a reservation to be able to land at the airport, which limits the number of inbound aircraft, and when traffic backs up at an airport, inbound aircraft are held on the ground at their departure airports until controllers see that slots will be available.[11] Reservations still could be used in a decentralized system. Is flow control necessary? If so, keeping an element of centralized control in a decentralized FFR system would be required.

[11] This flow control has almost eliminated aircraft entering holding patterns. Before flow control, arriving aircraft at congested airports would routinely be put into holding patterns to wait for their turn to land. Now, instead of costly holding in the air, the hold takes place on the ground at the departure airport.

Another possibility would be to use ATC as a gatekeeper at the entry points into airport traffic patterns. Instead of controlling the entire flight, controllers would manage the transition from en route free flight into the traffic pattern, assigning airborne aircraft entry times.

The ideas presented suggest possibilities for moving toward a decentralized system of air traffic control that would enhance the ability of aircraft to efficiently carry out their missions and increase the capacity of the ATC system.

Uncontrolled Airports

Most airports do not have control towers, leaving the responsibility of managing conflicts with other aircraft to pilots. The United States has 374 airports with control towers out of a total of about 19,000 airports.[12] The airports with control towers tend to be the busiest, and they tend to have commercial airline operations. To see how FFR might work at airports, consider the way air traffic now works at airports without control towers and try to envision whether this system could be scaled up to busier airports.

Traffic is managed at uncontrolled airports through radio communication among aircraft, and often from aircraft to a ground station, along with recommended flight procedures that aircraft can follow to minimize conflicts. At uncontrolled airports, aircraft are not required to have radios, so although many aircraft can communicate among themselves via radio, some may be incapable of doing so. And although there are recommended procedures for traffic patterns, taking off, and landing, those procedures are not required, even though following them helps coordinate traffic.

[12] See US Department of Transportation, Bureau of Transportation Statistics, table 1-3, "Number of U.S. Airports," accessed September 27, 2016, http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_03.html.

Pilots like to take off and land their aircraft into the wind because it minimizes ground roll. Thus, in many cases, wind direction will determine which runway is preferable for takeoffs and landings. Aircraft can fly a standard traffic pattern (recommended but not required) that will line up aircraft that are approaching an airport to land. Landing aircraft have the right-of-way over departing aircraft. In addition, many uncontrolled airports will have someone on a radio on the ground who can provide advisories to aircraft regarding which runway is being used and whether there are other aircraft in the area. All this advisory frequency does is pass information among pilots. It is not a control tower, and in many cases the person on the ground cannot even see the runway or other air traffic.

This process is completely decentralized. All aircraft movements are determined by the pilots without any direction from the ground—or anywhere else—and it works well. Pilots may have information from the ground, but they make their own decisions. As with traffic on a highway, it is a spontaneous order in which coordination is facilitated by a set of rules. Could this process be scaled up to work at busier airports and at airports that have a larger number of faster aircraft?

With the increase in the number of small jets in the general aviation fleet, smaller uncontrolled airports already have a mix of slow and fast traffic: jets that move at airliner speed and much slower propeller aircraft. The issue would seem to be the level of congestion rather than the potential for an airport to accommodate traffic of different speeds. Indeed, traffic at most of the busiest airports tends to be almost entirely jet airliners that all travel at the same speed. A challenge is that they move fast and require more separation from each other, but ADS-B enables them to see each other electronically and more reliably than smaller aircraft that lack such equipment and are trying to see each other visually.

Here is one possibility for FFR to replace ATC at busy airports. These airports already have standard traffic patterns that controllers direct aircraft to fly, so a point could be designated to enter the standard pattern, and aircraft would enter the pattern and land in the order that they arrived at the designated entry point. At uncontrolled airports now, the standard pattern is recommended but not required. It would be a small step to designate some airports as having required traffic patterns, with aircraft flying those patterns and using ADS-B for separation. Drones as well as piloted aircraft could coordinate with each other using this system, which would be entirely decentralized.

ADS-B Data Reliability

Another issue to consider is the data reliability of ADS-B. Aircraft should be able to deliver reliable GPS data on their positions, but all data are broadcast digitally from the aircraft itself, and the receiving aircraft has no way to verify the data. It is possible that someone could broadcast erroneous data—perhaps intentionally. Imagine, for example, a hacker delivering false data indicating that several aircraft are converging on an actual aircraft, thus causing the aircraft to take unnecessary evasive maneuvers and perhaps even overwhelming and confusing the aircraft's own ADS-B computers.[13] The current system, relying on ground-based radar, would not allow such an event because the aircraft does not report its own position (except for its altitude), whereas ADS-B relies only on the aircraft's broadcasting of its own position.

[13] A story briefly made the news that claimed that a computer expert hacked into an airliner's flight control system through the plane's on-board entertainment system and caused the aircraft to change course. The story is dubious because one would think that the aircraft's flight control systems would be completely isolated from its entertainment systems. The story is difficult to verify because such flight control systems are proprietary. The ADS-B communication protocols are not, however, so false ADS-B broadcasts could be made by anybody who has the equipment (which is commercially available) and the know-how to manipulate it. See Elizabeth Weise, "FBI: Computer Expert Briefly Made Plane Fly Sideways," *USA Today*, May 16, 2015.

The upcoming 2020 rules require aircraft to retain their current transponders, which in addition to providing a back-up system to ADS-B also provides ground controllers with data not broadcast by the aircraft to verify its location. If one is concerned about malicious interference, the current TCAS system may be more reliable in that regard than ADS-B. New technologies might also be developed to ensure the reliability of aircraft-to-aircraft data transmissions. Just as secure protocols have been developed for communication over the Internet, public-key data encryption could be developed to verify broadcasts, and networks using the existing cellular telephone infrastructure or an entirely new system could be developed. Although these are interesting ideas, history has shown that the FAA is extremely slow in introducing new technology, so ADS-B may be the technological limit for the foreseeable future, not because better technology cannot be envisioned, but because of the glacial pace at which it tends to be integrated into the ATC system.