NASA/CR–20210026446

State of the Industry: UAS Sensor Review

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HF Designworks, Inc.

September 2021

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Acronyms and Definitions

3D	three-dimensional
3DIS	3D Imaging Systems
ACAS X	Airborne Collision Avoidance System X
ADS-B	Automatic Dependent Surveillance-Broadcast
AESA	Active Electronically Scanned Array
AFRL	Air Force Research Laboratory
AGL	above ground level
AI	artificial intelligence
ATC	air traffic control
BVLOS	beyond visual line of sight
C2	Command and Control
DAA	detect and avoid
DSS	Discovery and Synchronization Service
DVE	degraded visual environment
DVEPS	Degraded Visual Environment Pilotage System
EMI	electromagnetic interference
EO	Electro Optical
EO/IR	Electro-Optical/Infrared
EWS	early warning system
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FLV	Future Vertical Lift (U.S. Army program)
FPV	first person view
GA	general aviation (non-military, non-airline aircraft and operations)
GBDAA	ground based detect and avoid
GHz	Gigahertz (thousands of MHz)
IFR	instrument flight rules
IR	infrared
kg	kilogram
km	kilometer
LAANC	Low Altitude Authorization and Notification Capability
LiDAR	Laser Detection and Ranging
LS	Life Safety
MEDEVAC	medical evacuation
MHz	mgahertz (million Hertz)

mm	millimeter
MOPS	Minimum Operational Performance Standards
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
OPV	optionally piloted vehicle
radar	radio detection and ranging
RF	radio frequency
SIO	NASA’s Systems Integration and Operationalization program
SOAR	Special Operations Aviation Regiment
sUAS	small unmanned aircraft system (0.55 to 55 pounds, 0.25 to 25 kg)
SWaP	size, weight, and power
TCAS	traffic collision avoidance system
UAM	Urban Air Mobility
UAS	unmanned aircraft system
UPS	United Parcel Service
USAF	United States Air Force
USAFRL	United States Air Force Research Laboratory
UTM	UAS Traffic Management
VFR	visual flight rules
VMC	visual meteorological conditions

State of the Industry: UAS Sensor Review

Scott Scheff[1]

1. Executive Summary

This report is a follow on from HF Designworks' 2018 report on state of the present and state of the art sensor technologies as they related to ground based detect and avoid (GBDAA) systems for unmanned aircraft systems (UAS). In this update, HF Designworks again looks to UAS test sites, manufacturers, vendors, and users to identify the latest sensor technologies covering not just GBDAA but additional UAS sensor types, including airborne.

For this latest report, the following sensor types were reviewed as well as a few that don't quite fit within the first five categories:

- Electro-Optical/Infrared (EO/IR)
- LiDAR
- Radar
- Radiofrequency (RF) scanner
- Acoustic
- Other sensor types

From our interviews and research with various organizations and individuals, we found both interesting new technologies as well as improvements to many technologies first reviewed in 2018. Compared with our 2018 findings, many of the new technologies have helped produce sensors that are smaller, lighter, require less power, and have better range and resolution than those discussed in 2018.

However, challenges still exist. There is no single currently available and Federal Aviation Administration (FAA) approved sensor suite that can adequately provide complete detect and avoid (DAA) capabilities to meet the needs of UAS beyond visual line of sight (BVLOS) in the civilian airspace.

Additionally, while technologies such as artificial intelligence (AI) hold promise, interviewees expressed uncertainty around the investment and development of AI-capable technologies because of the lack of a FAA AI regulatory framework. Conversely, the FAA is reluctant to produce requirements for AI without seeing the technology proven to be safe through extensive testing. This creates a significant "Catch-22" for the development of AI specifically tailored for UAS DAA.

Meanwhile, unregulated sensor technology is rapidly advancing, with development of increasingly capable yet smaller, lighter, and lower cost sensors that use machine learning for object detection on small, consumer-level UAS. This technology is not being heavily adopted on the larger UAS more frequently used by our interviewees, primarily due to the uncertain regulatory environment.

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[1] HF Designworks, Inc.; Boulder, Colorado.

As a path forward, we recommend identifying systems that integrate multiple sensors (such as a combination of air and ground) as the best method for the most reliable and efficient DAA, as well as encouraging standardized rules and requirements from the FAA on what is necessary for UAS flight in the civilian airspace.

Our complete findings and review are included in this detailed report. Additionally, for this latest work effort, we spoke with at least one contact at each of the following organizations listed in Table 1.

Table 1. Organizations Contacted

Organization	*Sensor/User Type*
American Aerospace	Manufacturer
Aurora Aerial	Integrator
Aurora Flight Sciences - Boeing	Manufacturer
Bell Flight	Manufacturer
Black Swift Technologies	Integrator
Burns Technologies	LiDAR
DeTect	Radar
Echodyne	Radar
FAA	Regulator
Fortem	Radar
GeoCue	LiDAR
Hesai Tech	LiDAR
Hover	Integrator
Iris Automation	EO/IR Cameras
Lightpath Technologies	Optics manufacturer
LightWare LiDAR	LiDAR
MAPIR Camera	EO/IR Cameras
MIT Lincoln Labs	Regulator
MITRE	Regulator
North Dakota UAS Test Site	Test Facility
Northrop Grumman	Manufacturer and Research
NSION	Integrator
Raytheon	Manufacturer and Research
RedTail LiDAR	LiDAR
ResilienX	Software
Sierra Nevada	LiDAR
Skysense	Anti-UAS technology
SRC	Radar
U.S. Army	Airborne system testing, DVEPS Project SOAR, LiDAR project
U.S. DOT VOLPE	Regulator
USAFRL	GBDAA
Virginia Tech	Test Facility
Xwing	Integrator

2. Project Background and Importance

HF Designworks, Inc. worked with the National Aeronautics and Space Administration (NASA) in 2018 to develop a report describing the state of the industry for GBDAA systems for UAS. During that effort, HF Designworks met with most of the FAA approved UAS test sites as well as interviewed several GBDAA vendors. Results of this work were both submitted to NASA and presented to RTCA's SC228 Detect and Avoid working group.

In 2021, NASA requested that HF Designworks update that report, furthering the research by identifying what has been improved in terms of sensor capabilities and identifying what challenges still remain. This new report expands the focus beyond just GBDAA to include all relevant UAS sensors, which includes airborne sensors; where due to greater SWaP challenges back in 2018, were not as prolific as they are today.

While this report discusses several ancillary issues related to our identified sensor technologies, including the regulatory framework and industry concerns, the report is focused on presenting the state of the industry of sensors capable of in-air use on various UAS aircraft, with a focus on DAA functionality.

HF Designworks researched approximately 100 companies and individual technologists for this latest effort. We interviewed more than 40, discussing publicly-available information related to aviation sensor technology (note that to have the largest audience receiving this information, all vendors, users, and test sites were specifically told not to discuss anything that was not considered distribution A: Public Release: Distribution Unlimited).

3. Technology Overview and Observations

3.1. Summary

A wide variety of sensors were investigated, including radar, EO/IR, Laser Detection and Ranging (LiDAR), acoustic, and camera. During our process we spoke with end users, manufacturers, integrators, and test sites. We revisited most of those we spoke with in 2018 and added new companies, organizations, and individuals. Several key findings from this work are:

- In most cases, today's newer sensors are smaller, lighter, require less power, and provide larger range and higher resolution than the sensors we reviewed in 2018.
- Sensor technology is rapidly progressing and several companies show promising DAA capability. However, no single commercially available on-board UAS DAA technology has been fully approved by the FAA (need to demonstrate sufficient range, reliability, accuracy, and capability for all commonly anticipated flight conditions; this is especially true for small unmanned aircraft systems [sUAS] due to their limited payload capacity and power).
- In addition, there are regulatory hurdles with integrating a combination of sensors for a complete on-board UAS DAA solution (sensors, software, and algorithms/artificial intelligence). Many of the manufacturers we spoke with expressed concerns about an unclear regulatory environment which, in their words, has not defined acceptable DAA standards or acceptable contributing technology.
- AI is top-of-mind for many manufacturers and integrators but the barriers to developing robust AI currently relegate most technologies to on-board or ground-based algorithmic processing and some nascent ground-based AI. Additionally, the lack of a defined regulatory environment clearly stating DAA requirements is stymying AI development. As we were told by several sensor manufacturers we interviewed—interested parties are discouraged from

investing resources in efforts to achieve an unknown goal without clear guidelines as to how and when AI will be permitted in Life Safety calculations.

- While we have observed an improvement in sensor technologies since 2018, it's primarily incremental betterment and not "order of magnitude" improvements. In addition to greater economic factors, including the Covid-19 pandemic's effect on work force staffing and the ability to get materials/parts, we were told by several individuals we interviewed that companies can't get the funding to research and develop sensors when there is not clear information on what requirements those sensors will need to meet. Simply put, and especially for smaller businesses that are more apt to rely on venture capital funds, venture capitalists don't want to give money to technologies with a long lead time and that, at the end of the day, might not be usable if they don't meet future regulations.

3.2. Sample Use Cases

From the manufacturers, testers, and users we spoke with, both air and ground sensors are being used in a variety of ways. We offer the following use cases as examples of sensor types, capabilities, and how they are being used today:

- Use Case #1: Fire Departments and Search and Rescue
- Use Case #2: Degraded Visual Environments
- Use Case #3: Renting Sensors for 3D Mapping
- Use Case #4: Northrop Grumman's Firebird Optionally Piloted Vehicle (OPV)
- Use Case #5: Plug-and-Play Surveying and Mapping Cameras
- Use Case #6: AiRanger pipeline patrol UAS Test

Additional discussion of each Use Case is provided in the following sections.

3.2.1. Use Case #1: Fire Departments and Search and Rescue

Fire departments are using UAS to identify hot spots in wildfires as well as for search and rescue purposes. UAS capable of autonomous DAA (in this case, using Iris Automation sensors) were successfully tested in rural areas using infrared thermal detectors to find test victims and the City of Reno (Nevada) Fire Department has tested UAS to help rescue people who fall into fast-moving local rivers. The use of UAS has been shown to allow quicker response times, faster identification of the rescue site (as well as exact subject location), and greatly reduce risks to first responders.

3.2.2. Use Case #2: Degraded Visual Environments

Sensors such as Burns Technologies' multi-function LiDAR can guide rotorcraft pilots during potentially high-risk landings in degraded visual environments (DVE), including darkness and zero visibility brownout conditions. An enroute option provides real-time day/night, all-weather visualization of the flight path environment, including terrain, buildings, towers, trees, and wires/cables. Currently available for manned aircraft, the technology is being further developed for use by autonomous UAS.

3.2.3. Use Case #3: Renting Sensors for 3D Mapping

Sensors are seeing more availability to the masses. In one case, GeoCue concluded LiDAR systems are better than photogrammetry for precision mapping, but LiDAR has been prohibitively more expensive. Thus, they created a LiDAR imagery system rental offering called True View to ease the barrier to entry for high precision three-dimensional (3D) mapping. True View 3D

Imaging Systems (3DIS) have a wide range of industry applications, such as oil and gas line survey, mining, infrastructure, land development, construction, and utilities inspection.

3.2.4. Use Case #4: Northrop Grumman's Firebird Optionally Piloted Vehicle (OPV)

Optionally piloted platforms are gaining traction where there may be a need for a platform to serve as both long duration unmanned as well as manned configurable. Northrop Grumman, for example, is currently operating a handful of Firebird dual-role optionally piloted platforms. The aircraft, with its 79-foot (24 meter) wingspan and weight of 7,100 pounds (3,200 kg), can be flown with manned pilots in the cockpit or converted to completely autonomous flight capability in less than four hours.

Designed for intelligence-gathering capabilities, the Firebird can remain airborne for up to 30 hours (in autonomous configuration) at an altitude of 25,000 feet (7,800 meters). The 1,700 pound (770 kg) payload—when autonomous—has 24 available sensors which include infrared sensors, radar, high-definition video, ground signal interception, and payload modules. The modules are designed to be rapidly exchangeable to support both manned and unmanned flight.

Firebird's size, performance, and capabilities are good indicators of what to expect when larger UAS are approved with the ability for BVLOS and long-endurance flights. This aircraft is primarily intended for high-altitude surveillance, including wildfire monitoring. The concept of an optional pilot for reduced crewing is not only for civilian space; military programs such as the next generation helicopters of Future Vertical Lift are looking at initially having semi-autonomous rotorcraft with reduced crewing and then the desire to transition to fully autonomous rotorcraft in later fielding increments.

3.2.5. Use Case #5: Plug-and-Play Surveying and Mapping Cameras

MAPIR has developed configurable plug-and-play cameras for surveying and mapping. Their cameras are designed to meet the need for compact multispectral image sensors that are used for high quality surveying and mapping photogrammetry. MAPIR's cameras are lightweight so they can be flown on small UAS. Their "Kernel" micro modular cameras can be configured 67 different ways with 31 types of filters. The filters can capture different surveying information, such as agricultural crop health and yield in addition to terrain elevation.

3.2.6. Use Case #6: AiRanger pipeline patrol UAS Test

In February, 2021, American Aerospace Technology worked with NASA to successfully demonstrate their AiRanger Class III UAS as part of NASA's Systems Integration and Operationalization (SIO) demonstration work. The flight started near Bakersfield, California, and flew at altitudes up to 2,000 feet (610 meters) on a predetermined flight path to inspect a pipeline. The two-hour flight covered 30 miles, escorted by a manned general aviation (GA) aircraft.

In addition to demonstrating the UAS's ability to perform pipeline patrols, a task often currently accomplished by manned aircraft, the real-world test provided significant data for analysis of the DAA and Command and Control (C2) systems.

DAA capabilities were provided by Echodyne (using their ground-based radar) and Sagetech Avionics [Automatic Dependent Surveillance-Broadcast (ADS-B)]. The AiRanger uses radar, cameras, and ADS-B for DAA as they perform a manned-aircraft style mission, but using an unmanned aircraft.

3.3. Examples of UAS at FAA-Approved UAS Test Sites

3.3.1. New York UAS Test Site

The New York UAS Test Site is one of the more capable of the seven FAA-sanctioned UAS sites and uses a combination of sensors for airspace surveillance systems, including ground radars and ADS-B. The use of multiple sensors gives the New York UAS Test Site the ability to monitor air traffic across a 50-mile (80 kilometer) corridor. The test site is managed by the NUAIR (Northeast UAS Airspace Integration Research) Alliance, Inc., a New York based nonprofit that is responsible to the FAA and NASA for conducting and overseeing UAS operations throughout the test site.

3.3.2. North Dakota Test Site

North Dakota's FAA-approved UAS test site employs several methods to track aircraft within their area of concern, but primarily relies on ground-based radar due to the size of the areas they monitor. Flights typically operate in the 500'–8,000' AGL airspace and they fly in ideal visual environmental conditions, meaning without rain, snow, fog, or smog.

Historically, they've used DACER 11 ground radar to monitor General Atomics' MQ-1 and MQ-9 large UAS platforms, and have also flown Northrop Grumman's large UAS Firebird (mixed use autonomous, or piloted) aircraft without a chase plane.

The North Dakota Test Site is also conducting flights inside cities using Echodyne radars (both ground and air based), including tracking MEDEVAC helicopters from the roofs of local hospitals.

Another sensor manufacturer, Fortem, is providing shorter-range radar at the North Dakota test site.

3.4. Future Use Cases

While commercial use of sUAS for delivery of retail goods is already here (in select areas/environments), this use case will likely become more prevalent in the near future. The trend is also accelerating due to the Covid-19 pandemic. With UAS providing delivery services, companies expect significantly reduced costs—per Dronesvilla.com (7/2020) deliveries could cost as little as 88¢ each via UAS delivery versus the current $6–$8 each that restaurants are paying for human drivers and third-party delivery services.

CVS Pharmacy has tested and successfully conducted commercial prescription medication delivery via United Parcel Service (UPS) UAS in Cary, North Carolina. Prescription medication was delivered to both a private home and a retirement center, where the UAS hovered at approximately 20 feet (6 meters) while lowering packages to the ground. The flights were performed autonomously, though human UAS operators were closely monitoring. Eventually this type of use case will be able to be performed completely autonomously; without human oversight.

In the food world, El Pollo Loco is testing "door to backyard" UAS delivery. Other companies are testing UAS delivery to unoccupied parking lots with manned ground delivery vehicles handling the "final mile." Under this use case, UAS have been able to fly at an elevation of 200 feet (32 meters), carry up to 6.6 pounds (3 kg) of food, then hover and lower the payload from 80 feet (24 meters). Significant testing for these and other services will be necessary to adequately work through major cities where dense populations and challenging traffic are concerns.

4. Sensor Technology Findings

4.1. Overview

For any of the above use cases to be viable (especially the future civilian airspace examples), a multitude of sensors, software, and in many cases, automation will need to be utilized. From our industry review, we identified three primary sensor technologies (LiDAR, radar, and EO/IR optics) as well as less common technologies, (some still in development) that we feel merit inclusion. While acoustic could be considered a fourth sensor technology, its use has been limited. Many of those interviewed were aware of acoustic sensors, though very few had actually used the technology and those who did felt it was not ready for "prime time."

The following section includes more detailed discussions on various technologies, based on research and interviews with manufacturers and users, and includes a pro and con table for each sensor group.

4.2. Sensor Comparison Summary

Table 2 is a sensor comparison summary providing benefits, drawbacks, and approximate cost for the various sensor types we evaluated. Following Table 2 are Figures 1 and 2 which provide a comparison of radar range. Figure 1 compares the radar range of small, medium, and large radar and how far out they can detect small UAS, medium UAS, and small GA aircraft. Figure 2 compares sensor range, evaluating LiDAR, radar, and camera sensors as they detect ground terrain (for LiDAR), small UAS, medium UAS, and small GA aircraft (for radar), and small GA aircraft (for camera).

Table 2. Comparison of Sensor Technologies

	Benefits	*Drawbacks*	*Cost*
Radar	Works in degraded visual environments. Long Range (2 km for small aircraft; 1 km for UAS).	Highest cost, weight, and power requirements. Mostly used for GBDAA.	\$5K–\$1M+
EO/IR	Low weight, cost, and power requirements. Variable range, capable of long-range detection (range depends on optics).	Limited to clear airspace conditions. 3D requires multiple sensors.	<\$1K–\$100K
LiDAR	Works in slightly degraded visual environment. Better than cameras for estimating object range. Technology rapidly improving due to autonomous car industry.	Range (<200 meters). More expensive than cameras. IR Spectrum challenge (eye safety limit, potential to trigger aerial threat detection systems).	<\$K–\$100K
RF scanner	Works in degraded visual environments. Long range (up to 3km). Detailed UAS information.	Only detects known commercially available UAS RF signatures. Requires multiple sensors to be able to specifically locate UAS.	\$1K–\$10K
Small UAS short range sensors	Lowest cost. Technology rapidly improving.	Consumer grade. Short range.	<\$1K
Acoustic	Light weight/cost.	Emerging technology; not enough adoption yet.	\$1K–20K (estimated)

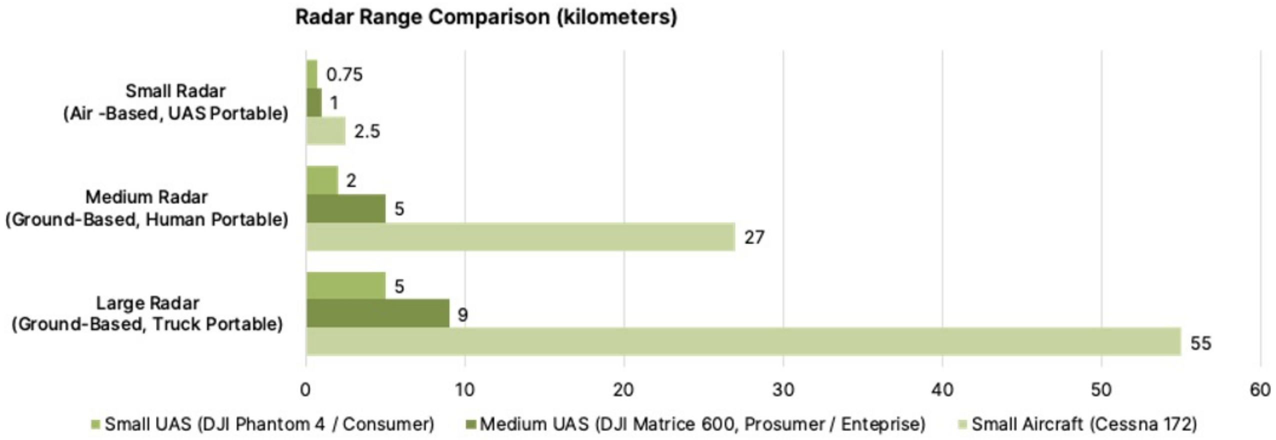

Figure 1. Radar range comparisons.

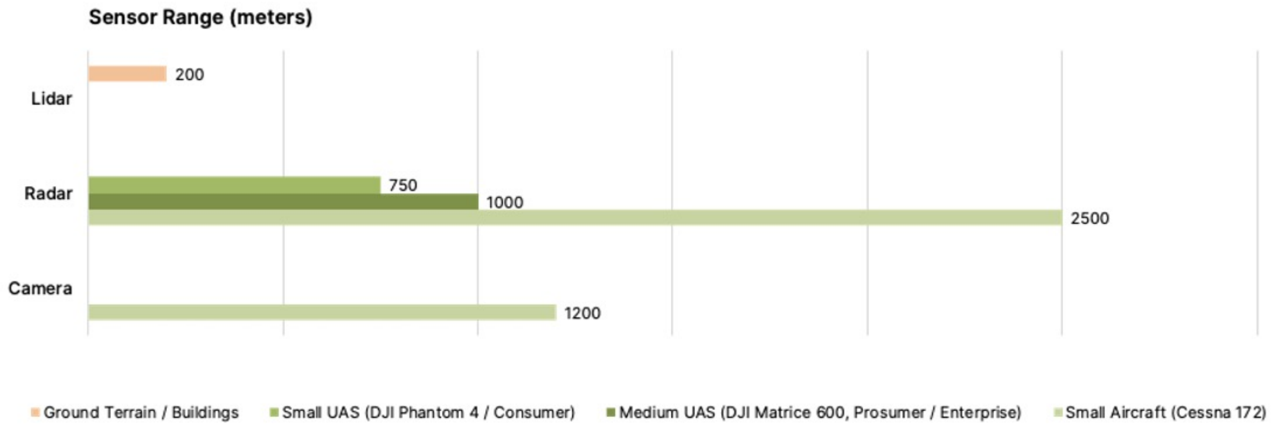

Figure 2. Sensor range comparisons.

4.3. Laser Detection And Ranging (LiDAR)

The pros and cons of LiDAR are shown in Table 3.

Table 3. LiDAR Pros and Cons

Pros	*Cons*
Relatively low cost. $$	Limited range for DAA use due to laser scatter and resolution issues - less than 650 feet (200 meters).
Small size, Weight, and Power (SWaP) demands.	Relatively high degradation in snow or dust (brownout) DVEs.
Current increasing demand from the automobile industry is driving rapid innovation.	Significant tradeoffs between detection range and quality of target resolution.
Fully viable in darkness.	
Can create 3D mapping “cloud point” solutions [useful for takeoff/landing in degraded visual environments (DVEs)].	
Can be relatively inexpensive and prices are dropping each year, due in large part to automotive demand.	

LiDAR appears to be the most popular and accessible technology in terms of airborne based UAS sensors, especially for the smaller UAS that are not going to have the payload and power capacity for the larger radar systems. Part of the reason for the popularity of using LiDAR is that research, development, and manufacturing costs are reasonable for even small companies; this is largely driven by the current growing research in the autonomous automobile industry. While retail pricing runs across a wide range, more and more lower-end units can be found costing less than $1,000, putting them in reach of most commercial and some prosumer and hobbyist UAS operators. Common LiDAR applications include mapping and surveying, with secondary applications growing for close-in navigation, landing site review (including for autonomous landing), and increasingly, applications for DAA.

Currently, the practical LiDAR navigation range remains limited to 260–650 feet (80–200 meters), which is insufficient for either DAA or navigation at speed in complex (low-level and/or high speed) environments. This range is useful however for cooperative situations where, for example, a UAS can deliver a payload to a manned ground vehicle or delivery person who then handles the last mile (or more literally, the last few blocks). LiDAR can be used to efficiently locate a QR code on a vehicle roof or landing banner, then safely control landing, and allow a safe departure after discharging its cargo. 3D LiDAR can also be helpful in identifying objects potentially obstructing safe landings including poles, wires, and rebar.

Due to the competitive automotive landscape, LiDAR technologies are developing rapidly with short lifecycles and advancing technology. Coming from our 2018 report, LiDAR has seen significant advancement in the past couple years, largely due to its increasing use as part of automotive systems. Today, LiDAR can be found in both assistive and autonomous roles. As one LiDAR manufacturer said: “Nothing we sell now will be current in two years.”

LiDARs on UAS can be relatively small, lightweight, and consume low power, so systems can fit into many UAS including sUAS. There are both fixed-aperture and, increasingly commonly, rotating systems that allow wider fields of view; up to 360 degrees.

LiDAR uses laser light at either 905 or 1550 nanometers. Laser light emissions are regulated as there are significant human eye safety concerns for participants, bystanders, and any personnel within the operating area. All the manufacturers we spoke with said they address these issues by restricting power levels, limiting wavelength spectrum, and/or other methods.

The following LiDAR systems were reviewed:

- Burns Technologies, LLC
- GeoCue Canada
- Hesai Technology
- LightWare LiDAR
- RedTail LiDAR Systems

4.3.1. LiDAR Technology Providers

Following are summaries of technology providers.

4.3.1.1. Burns Technologies, LLC

Formed in 2016 and based in Orlando, Florida. Burns Technologies makes eye-safe nose-mounted LiDAR for medium to large manned helicopters. Used for aircraft landing guidance in DVE, including darkness and brownout conditions. Also has enroute cruise navigation option for terrain/obstacle avoidance. Weight is 60 pounds (27 kilograms), >1650 feet (>500 meter) range, system scans 150,000 pixels per second with four hits per pixel.

4.3.1.2. GeoCue Canada

Founded in 2003 with locations in Huntsville, Alabama; Brisbane, Australia; and Toronto, Canada. GeoCue provides software, hardware, training, support and consulting services for LiDAR mapping, including production and data exploitation, and drone mapping. Heavy geo-spatial and mapping focus, especially involving LiDAR Point Clouds for all-purpose, Utility-grade, and Survey-grade 3D imaging.

4.3.1.3. Hesai Technology

Founded in 2014, manufactures 3D laser sensors for robotics, including UAS. 500+ employees, headquartered in Shanghai, China. One of their more popular units is the Pandar XT which has 32-channels, 400 foot (120 meter) range, size is 4x4x3 inches (100x103x76 millimeters), 10 watts. 640,000 data points per return. They are releasing a 64-channel version, with proportionally higher-resolution, and offer several other LiDAR units.

4.3.1.4. LightWare LiDAR

LightWare LiDAR produces very compact, lightweight LiDAR units. Founded in 2011, headquartered in South Africa with a Colorado office. Multiple small units with different features including focal lengths and spectral sensitivity. Units weigh 0.35 to 10 ounces (10–270 grams) with ranges of 165-330 feet (50–100 meters). 905 nanometers. In development is a 5,000 foot (1,500 meter) range unit. Customers often use arrays of multiple sensors. Used in UAS and other applications, including vehicle detection by automated parking meters.

4.3.1.5. RedTail LiDAR Systems

A division of 4D Tech Solutions, RedTail was started in October of 2019. Based in Fairmont, West Virginia. RedTail manufacturers the sensors, develops the analytics software, as well as performs the integration for UAS. System-agnostic; uses any UAS and RedTail provides mounting, calibration, and testing. 4.2 pound (1.9 kilogram) unit about 9.4x4.6x4.6 inches (238x117x117 mm). 1550 nanometers, 330 foot altitude range, 400 kHz, 100 lines/second, 1 million points/second, 45 Watts.

4.4. Radio Detection and Ranging (Radar)

The pros and cons of radar are shown in Table 4.

Table 4. Radar Pros and Cons

Pros	*Cons*
Radar currently offers the largest range and highest resolution of the discussed sensor systems. For example, Cessna-sized* GA aircraft can be detected and identified at ranges exceeding 25 miles (40 kilometers).	Radar units are substantially larger and heavier than LiDAR units. Many sUAS may not be able to carry radar units, let alone radar and any worthwhile payload. This severely limits their viability on UAS at this time, especially since few larger UAS are regularly flying in the U.S. civilian airspace.
Radar systems, either airborne or ground-based, are typically part of more sophisticated solutions and may be just one component of a more robust DAA/navigation system.	Can be expensive ($$$$$; can be in excess of $1M).
Good ability to get imagery in darkness, fog, rain, cloud, and other DVE.	

**The traditional GA lightplane target size is equivalent to a Cessna 172 Skyhawk: aluminum construction with a 36 foot (11 meter) wingspan; 27 foot (8.3 meter) length; nine foot (2.7 meter) height; flying weight approximately 2,500 pounds (1,130 kg); and cruise speed of 125 miles per hour (200 kph).*

Radar remains the most robust and useful system for DAA, but its size, weight, power draw, and costs preclude its use on most UAS less than 1,000 pounds (450 kg). Therefore, it is not commonly deployed as an airborne based system.

Ground-based radar remains a highly desirable and powerful tool, though there are many limitations on its viability and utility, especially in civilian urban environments. Ground-based radar systems, either independent or integrated with control systems for a UAS fleet, are commercially available as proven, effective technology.

Ground-based radar is heavily used for air traffic control (ATC) in the NAS. Some eighty percent of US air traffic is now controlled using Raytheon Technologies' Standard Terminal Automation Modernization and Replacement System (STARS). The system is used at airports and Terminal Radar Approach Control facilities to oversee air traffic up to 60 miles (100 km) around airports and up to 14,000 feet (4,300 meters) altitude.

Raytheon's Skyler is a 3.3 foot (1 meter) square, low-power, Active Electronically Scanned Array (AESA) software-defined radar, used in the STARS system. Skyler can be placed on cell towers and buildings to monitor sUAS traffic and other airborne targets. A bus-mounted mobile system, called SkyVision, includes a towable radar array.

The USAF flies large UAS, especially the Global Hawk and Predator, on dedicated test ranges in remote areas—getting the UAS to these areas can require 25-plus miles of flying in the NAS. In the past, the USAF did DAA manually with ground spotters every few miles and manned chase planes escorting the UAS.

STARS and Skyler were modified so radar data could be used to alert Air Force UAS operators and other staff of airborne obstacles. This GBDAA was subsequently approved by the FAA to fly the UAS BVLOS, with systems installed at Cannon Air Force Base in New Mexico and Beale Air Force Base in California.

When installed on suitably sized UAS, airborne based radar units are typically installed in the front of the aircraft to provide an unobstructed view forward. This may create packaging challenges with repurposing existing aircraft, such as formerly manned fixed-wing or rotary aircraft, and with multi-rotor UAS. Additionally, users have reported issues with radar units receiving EMI/RF interference in some UAS installations. As mentioned, radar units are typically substantially heavier, larger, and costlier with greater power demands than LiDAR or EO/IR units.

Additional radar systems reviewed:

- DeTect
- Echodyne
- Fortem Technologies
- SRC

4.4.1. Radar Technology Providers

Following are summaries of radar technology providers.

4.4.1.1. DeTect Inc.

Headquartered in Florida with offices in Canada, England, and China, DeTect specializes in advanced radar and other sensor technologies, including aircraft bird strike avoidance and wind turbine bird mortality. Their DroneWatcher system, released in 2016, includes RF sensors and radar for tracking and interdiction of sUAS and larger UAS. 500+ systems worldwide since 2003.

4.4.1.2. Echodyne Corp.

Based in Kirkland, Washington, Beam-steering radar for ground-based and autonomous machines. Electrically-scanned radar with low SWaP and in-house software. Markets include defense, UAS interdiction, and air taxis. In-air UAS radar uses multichannel K-band radar, size is 8.2x6.7x1.6 inches (210x170x40 mm), with 120° azimuth x 80° elevation sweep.

4.4.1.3. Fortem Technologies

Utah-based provider of counter-UAS radar and technology. Focused on securing ground targets from unauthorized UAS, either careless or hostile. Radar and software combine to monitor and respond. Also offer an interceptor UAS that integrates with their radar and overall system.

4.4.1.4. SRC

Founded in 1957 as a Syracuse University technology spinoff, SRC is an independent, not-for-profit R&D corporation. SRC manufactures multiple radar offerings, including military counter-UAS systems that include radar, early warning system (EWS), cameras, and a user interface to detect hostile UAS. They also have specialized offerings to detect small, low-flying aircraft.

4.5. Electro-Optical and Infrared Sensors (EO/IR)

The pros and cons of EO/IR sensors are shown in Table 5.

Table 5. EO/IR Sensors Pros and Cons

Pros	*Cons*
Optical sensors provide very human-accessible information with no processing: this easily provides well-understood feedback and visual information, especially valuable for conveying information to untrained observers.	Of the three major sensor technologies reviewed, EO/IR sensors suffer the most during DVE situations; whether darkness, dust, smoke, or precipitation. Typically, visual light sensors are "just barely better than human eyes," said one manufacturer, while IR can be tuned for somewhat better DVE penetration.
Inexpensive ($-$$)	

EO/IR sensors are ubiquitous for close-in navigation and route-finding, where they are extremely effective in clear-weather conditions. EO/IR sensors are also the most affordable of the sensor technologies, largely due to the vast amount manufactured for everything from doorbells to cell phones to automotive navigation. Most EO/IR sensors, however, are not well-suited to provide both the wide-angle views needed for navigation and the telephoto views desired for DAA identification. Like all sensors, EO/IR equipment requires robust software to provide anything more than visual information.

There are many lower-end, consumer-grade EO/IR sensors, including those used for first-person flying of hobby and very small UAS aircraft. These smaller UAS and systems may use one or multiple camera sensors for piloting/navigation as well as providing photography and video capability. These have high manufacturing volume, but low sophistication; the EO/IR cameras discussed here are more capable, more sophisticated, and more costly.

Like LiDAR, EO/IR cameras are often deployed in modules to allow for greater capabilities, including ranges of wavelength, resolution, and focal length. Like other sensors, cameras must have line-of-sight to their targets, so are often deployed at the front of aircraft or on a chin-turret.

SWaP specifications for EO/IR cameras vary depending on mission. Many units are quite compact and have low power requirements, while more sophisticated sensors are expectedly larger and heavier.

Note: Many consumer-grade UAS offer lower-end cameras for first person view (FPV) piloting and for hobby photography and video. Some higher-level UAS also use similar cameras as secondary payloads for photography and video. These cameras are not part of integrated systems for navigation, DAA, or other autonomous control systems and thus are not used by the people we interviewed.

The following EO/IR systems were reviewed:

- Iris Automation
- MAPIR Camera
- Teledyne FLIR

4.5.1. EO/IR Technology Providers

Following are summaries of EO/IR technology providers.

4.5.1.1. Iris Automation

California-based manufacturer of the Casia Detect-and-Avoid system. ~1200 meter range for small GA aircraft. 360° radial horizon, intelligent automation to identify intruders, track and avoid in daytime VMC (visual meteorological conditions). EO/IR cameras with machine learning and Computer Vision. Active with BVLOS programs. Integrates with many UAS airframes and autopilots. Recently released a version to augment manned aircraft safety by announcing the presence of UAS.

4.5.1.2. MAPIR Camera

Launched in 2015 from Peau Productions to manufacture compact, multi-spectral image sensors. Focusing on very small, modular units so nearly all UAS can carry an array of sensors. Provide multispectral image sensors with varying focal lengths. Recently introduced their Kernel2 universal array system for six different sensors covering a range of wavelengths.

4.5.1.3. Teledyne FLIR

One of the largest EO/IR sensor manufacturers, FLIR started in 1978 with airborne thermal (infrared) imaging systems. FLIR expanded throughout the commercial thermal imaging markets and was purchased by Teledyne Technologies in 2021. FLIR manufactures a wide range of sensors, primarily infrared. FLIR makes a wide variety of products for surveillance, reconnaissance, search and rescue, detection, targeting, and infrastructure protection.

4.6. Other Sensor Types

4.6.1. Acoustic

Acoustic sensors generate industry discussion but very few organizations are actively manufacturing and selling products. While very few sites and individuals interviewed have actually used acoustic sensors, nearly everyone interviewed said they were familiar with the concept. This technology does not appear currently viable as a primary DAA method; however, size/weight/power restrictions on sUAS where an array of sensors is needed may limit its adoption as a backup DAA method.

4.6.2. Consumer/Prosumer Short Range DAA Sensors

Consumer and prosumer grade sUAS provide short range DAA for less than 100 meters. The sensors used are typically a combination of ultrasonic sensors, LiDAR rangefinders, and cameras to detect obstacles and either alert the operator or adjust course to avoid the obstacle. For example, DJI includes collision avoidance on most of their consumer and prosumer level UAS, while Skydio offers fully autonomous mapping UAS that automatically avoid obstacles as they perform 3D infrastructure scanning operations.

4.7. Calibration, Tuning, Configuration, and Optimization

All of the above discussed sensors have substantial software componentry—they are true coexisting systems dependent on harmonious function between hardware and software. Optimizing these sensors for maximizing function and improving capabilities through configuration and tuning are high priorities for all manufacturers.

Calibration, tuning, configuration, and optimization are critically important to the usability and success of UAS technology, especially for DAA. To be most effective, sensors must be properly calibrated both by the manufacturer and in the field. Tuning involves modifying the configuration values of a sensor in order to detect a specific type of target: Good tuning will improve the probability of a detect while poor tuning will lead to none, or false, detects. LiDAR, radar, and EO/IR must each be configured for every detection mission—which can add complexity to a flight mission since certain requirements can be competitive.

While optimization is achieved when a sensor is properly calibrated, tuned, and configured for a given task, challenges include competing priorities since most sensor systems can only prioritize one detection parameter, often at the expense of the sensitivity or efficacy of others.

For example, a sensor can be optimized for detecting and tracking either larger or smaller targets. More emphasis on one can reduce the sensitivity to the other. Likewise, a sensor can either detect at a longer range or have a wider field of view but cannot do both at the same time. Multiple tracked objects at the same time also creates complications for sensor data analysis.

Fortunately, technological innovation is rapid. One user reported working closely with the sensor provider while in the field, extensively sharing data and discussing feedback to yield incremental improvements. A year later, the vendor offered this user a firmware upgrade that vastly improved the system's capabilities.

4.8. Artificial Intelligence (AI) and Machine Learning

Sensors create large amounts of data as they scan, which in many cases is ripe for the use of AI and machine learning to filter out data that is not needed, repetitive, false, etc. While algorithms are used by most vendors to improve sensor performance and data display to end users, there are several reasons AI and machine learning are not yet fully utilized by these sensor systems as currently implemented. Primary reasons include cost, available resources, and an unknown regulatory environment.

Many manufacturers stated the lack of a clear regulatory environment for DAA standards has limited their research and development. Several technologists and manufacturers commented that AI is “not approved for Life Safety” solutions, making them reluctant to invest in solutions that may be rejected by regulatory agencies, including the FAA and FCC.

Currently, requirements for UAS DAA are not well-defined. Anecdotally, there seem to be requirements for UAS to avoid only manned aircraft, with no requirements for DAA technology involving unmanned aircraft, birds (either individual or flocks), or other air or ground obstructions.

Some existing systems have capabilities to locate and assess potential landing spots, especially looking for hazards like vertical rebar, poles, towers, guy wires, cables, and other hard-to-see hazards. These are used both for UAS and to assist human pilots of manned aircraft, especially rotorcraft. Most of these capabilities are a side benefit of mapping technologies, especially LiDAR, and few companies are using AI or machine learning to augment these capabilities at this time; although the recognition that AI or machine learning could be used for augmentation is there.

4.9. Other Considerations and Additional Technologies

4.9.1. Regulatory Environment

Many of the technologists and manufacturers we spoke with for this report said they feel the unknowns and difficulties of the regulatory environment are critical limiting factors for technological development of sensors for UAS.

The FAA oversees all operations in the National Airspace System (NAS)—including manned and unmanned aircraft of all sizes, configurations, power plants, and operator types and skill levels. This wide-ranging responsibility can create a large and often slow-moving bureaucracy. Historically, the FAA has been conservative and most-focused on ensuring life safety for commercial passengers and non-flyers, and less on advancing technology.

“It’s hard to know what we are aiming for,” said one potential developer of autonomous DAA technology. His company is holding off moving forward in several technological areas until they know more about what paths the FAA will approve.

Many feel the UAS industry is on the brink of greatness—and has been for several years—as they have been waiting for the FAA to promulgate effective and, hopefully, efficient regulations. By design, the FAA’s process is detailed and can be relatively slow.

Interviewees said the current FAA regulations are too restrictive to allow for real-world UAS use. At this point, each BVLOS flight requires an individual FAA waiver; there are no public regulations for large-scale commercial UAS use; no DAA standards for any size UAS; nor has the manned aircraft primary training curriculum been upgraded to include UAS awareness.

Several people interviewed explained this lack of known regulatory framework has created significant difficulties attracting investment capital to grow their companies as well as getting company leaders to invest resources into an industry that does not yet have full commercial viability, nor a validated short-term path forward.

Many companies are interested in using AI to strengthen the speed and versatility of their DAA, navigation, and other autonomous flight issues. However, several technologists said they feel they are not able to do so. Reviewing recent RTCA Minimum Operational Performance Standards (MOPS) documents did not find any official FAA position on the use of AI for manned or unmanned aircraft, though several interview respondents believe the FAA may be extremely reluctant to allow AI in life safety issues due to the need for extremely robust failure modes.

4.9.2. Remote ID

While not sensor-related per se, the FAA will soon require nearly all UAS to provide publicly-available information about the UAS' location and the location of the remote operator. This is primarily focused on protecting the public by allowing law enforcement to identify UAS operators, though there are some areas that may provide useful information for UAS DAA.

Since the Remote ID mandate is not yet in effect, several key aspects remain unknown. These include effective broadcast/receiving ranges of Remote ID location information, as well as accuracy and reliability of the information.

Remote ID's stated primary function is to promote public safety by allowing citizen reporting and public safety official review of "suspicious" UAS in areas including "airports, heliports, prisons, military installations, nuclear facilities, large stadiums, and other critical infrastructure locations where a UAS could potentially pose an imminent threat to public safety."

Per the ASTM F3411–19 Standard Specification for Remote ID and Tracking, "Remote ID's objective is to increase UAS remote pilot accountability by removing anonymity while preserving operational privacy for remote pilots, businesses, and their customers. Remote ID is an enabler of enhanced operations such as beyond visual line of sight (BVLOS) operations as well as operations over people."

Use of Remote ID information for DAA and navigation, if even possible, is a side benefit and not a priority. Only the last of seven use cases in the ASTM Standard discuss navigation or DAA. Manufacturers must implement Remote ID on new UAS by September 2022, with all operators using Remote ID by September 2023.

None of the Remote ID information contemplates autonomous operation—everything refers to having a UAS operator. Urban autonomous delivery was not discussed. The specification also does not address long-distance remote UAS operators, such as the example of a large UAS doing pipeline patrol across Nebraska with ground control in a Texas facility. These larger unmanned platforms (Cessna-sized or bigger) may use ADS-B Out and other more robust ID and DAA tools; are likely to be largely autonomous; and will definitely need robust DAA and navigation capabilities.

Remote ID is described as a “car license plate” and supports privacy by sharing limited data, attempting to discourage “the use of remote identification as a means for ongoing surveillance over a wide area or to mine patterns of life for users of drone services.”

It’s worth noting the specification states information will be provided to very high-precision accuracy but also gives accuracy parameters covering extremely wide ranges. Since this is not yet implemented, it’s difficult to assess real-world accuracy.

Certainly, the high-precision location information could be extremely beneficial to a DAA system receiving Remote ID information; however, this location information must be provided with both sufficient warning and accuracy for the DAA system to respond and calculate safe avoidance navigation (ideally while continuing its mission).

The specification does not address larger or more complex UAS using ADS-B, “nor does it purport to solve ID needs of UAS for all operations. It does not purport to address identification needs for UAS that are not participating in Remote ID or operators that purposefully circumvent Remote ID.”

The ASTM document includes many statements of areas “beyond the scope of this specification” including:

1. “A typical user interface might be map-based with symbols for UAS in the area. However, the manner in which the information is presented is beyond the scope…”
2. “Remote ID Display Applications that integrate Broadcast and Network Remote ID data will be produced by industry; however, this also is beyond the scope…”
3. “Only approved USSs [UAS Services Suppliers] will be given access to the DSS [Discovery and Synchronization Service]. (The specifics of an approval process are beyond the scope…”

As background, there are two types of Remote ID: Broadcast and Network. Broadcast Remote ID transmits radio signals directly from a UAS to receivers in the UAS’ vicinity. Broadcast is for anywhere, especially poor or no cell/internet.

Network Remote ID uses WiFi (Channel 6 2.437 GHz or Channel 149 5.745 GHz only) or Bluetooth (Legacy 4.x and Long Range 5.x, 2402-2480 MHz) to broadcast through cellular networks to “commonly carried hand-held devices that have their own antenna” (smart phones with an app). Receiving equipment is not part of the specification and how exactly this will work is a frequent critical question about Remote ID’s function.

Remote ID includes distance-based limitations on what information is sent to observers. The calculation is complex and unclear, but it appears UAS location info may be blocked if the receiver is not in the “immediate” area. It is also difficult to determine practical transmission distance for Remote ID information. Additionally, physical Bluetooth and WiFi transmitter equipment must be added to UAS on or before the deadlines.

Bluetooth’s speed limitation is ~1 Mbps and has been tested to 1,320 feet (400 meters) in a rural environment, though RF interference will reduce this. Bluetooth5 has four times the range of Bluetooth4, and rural range can be ~1 km, though again RF interference will reduce this. There was no information on urban range testing, which could imply greatly reduced capability. For the specification’s power levels, Bluetooth4 will have a shorter range than Bluetooth5, which is in turn shorter range than WiFi.

WiFi offers more power and range, transmitting at 6 Mbps. Rural tests show ranges of +0.6 miles (+1 km) with the possibility of 2.5 miles (4 km). Again, RF interference will reduce this.

Relevant information transmitted by Remote ID includes:

- UAS ID.
- UAS type (not model-specific but general performance characteristics, including these from the official ICAO UA Type list. Additional types were added if they had unique flight characteristics):
  - 0: None/Not Declared
  - 1: Aeroplane
  - 2: Helicopter (or Multirotor)
  - 3: Gyroplane
  - 4: Hybrid Lift (Fixed wing aircraft that can take off vertically)
  - 5: Ornithopter
  - 6: Glider
  - 7: Kite
  - 8: Free Balloon
  - 9: Captive Balloon
  - 10: Airship (such as a blimp)
  - 11: Free Fall/Parachute (unpowered)
  - 12: Rocket
  - 13: Tethered Powered Aircraft
  - 14: Ground Obstacle
  - 15: Other
- Timestamp.
- Latitude and Longitude - Minimum resolution: 7 decimal digits (½ inch, ~11 mm).
- Height above ground level or takeoff location, Geodetic altitude, Pressure altitude (uncorrected barometric)—1 meter resolution.
- Geodetic Vertical, Horizontal, and Speed accuracy—specification states these are based on various ADS-B criteria, which is confusing since ADS-B is not expected to be available on the subject UAS. Horizontal accuracy ranges from 3 feet to 10 nautical miles (<1m to <18.5km) or unknown, Vertical accuracy ranges from 3 feet (1m) to 500 feet (150m) or unknown, and Speed accuracy ranges from <0.3m/s to <10m/s or unknown.
- Speed—within 0.56 mph 0.25 m/s.
- Vertical Speed—up to 200 feet per second (62 m/s), no resolution stated.
- Track Direction—within 1 degree.
- Operator info: Latitude, Longitude, Location Type, Operating Radius, Minimum altitude, maximum altitude, start and end times.
- Authentication of UA identity.

4.9.3. ADS-B Out Transponders and Related Information

Since January 1, 2020, most manned aircraft in the National Airspace System (NAS) are required to transmit augmented information via Automatic Dependent Surveillance-Broadcast (ADS-B) transponders.

Following the mandate, subject aircraft now automatically broadcast information every second. Information includes aircraft "squawk code" (a tracking number), aircraft size and performance capabilities (including speed), registration information, GPS latitude, longitude, and altitude, plus pressure altitude. Since location is broadcast every second, heading and velocity can be determined within a few moments.

This additional information is designed to greatly increase the capacity of the NAS and allow higher density of aircraft under ATC. ADS-B Out inherently provides greatly enhanced abilities for See and Avoid with manned aircraft, and, likewise, for DAA using UAS.

Most sUAS are exempt from the ADS-B requirement and furthermore are not permitted to broadcast ADS-B information due to concerns about saturating the available bandwidth. Larger and further-ranging UAS are expected to participate in ADS-B Out, though those rules have not yet been promulgated.

Prior to the Mandate, manned aircraft transponders responded to radar queries with a squawk number identifying the aircraft and its pressure altitude. The ATC tracking radar provided the aircraft location. (Many aircraft did and still do use a general squawk code if they are not flying IFR or on an active flight plan—the “1200” code accounts for roughly half of GA flights.)

Any aircraft operating in an area where transponders are required is now required to have ADS-B Out. Exceptions include gliders/sailplanes, ultralights, and older/more basic aircraft without an electrical system. While a relatively low percentage of flights, these exceptions are significant for any DAA system using ADS-B Out data.

Participating aircraft can also take advantage of ADS-B In, which collects and presents this data to many varieties of manned flight applications ranging from iPad applications like ForeFlight to sophisticated in-panel cockpit displays.

User privacy is notably different for UAS-oriented Remote ID and ADS-B Out for manned aircraft. ADS-B Out provides detailed information on equipped aircraft flights, including aircraft identification information. Organizations like FlightAware and others make that information freely available world-wide via the Internet by matching the broadcast information with publicly available aircraft registration information provided by the FAA website. This includes specific information on the aircraft’s owner and address—which can be extremely vexing to many manned aircraft owners and operators.

5. Summary

Examining today’s sensors compared to the GBDAA sensors discussed in our 2018 report, while there have been technological improvements and additional flight testing of UAS and sensors since 2018, there still remain some challenges to UAS in the civilian airspace. There is currently no single airborne sensor that can provide sufficient DAA capabilities. Most likely, achieving safe DAA for UAS in the civilian airspace will require sensor fusion with cooperative input from a variety of sensors, both ground and air based.

Some sensors are maturing faster than others. With the growing demand for autonomous ground vehicles, there is a large need for LiDAR technology in the automobile industry. This need is fueling rapid and large advancements in LiDAR development—in some cases the sensor technology has only a 12–18 month product lifecycle.

Similar to 2018 findings, the regulatory environment continues to be a challenge. The FAA is hesitant to approve emerging UAS technologies without a proven safety test record. Conversely, without that approval, manufacturers and investors are hesitant to pursue further development of emerging technologies that could assist UAS (such as AI) due to uncertainty and lack of regulation.

6. Path Forward

Sensor technologies will continue to develop, as will their applicable UAS use cases. We recommend that interested parties continue to follow up with the test sites, technologists, vendors, and users discussed in this report to make sure public information remains current and distributable so the industry as a whole can better work together on the challenges of UAS in the civilian airspace. Additionally, the FAA should work with industry to promulgate rules and policies for commercial UAS BVLOS flight in the civilian airspace. Ensuring industry members understand the requirements for successful UAS will help drive technology (and research and development dollars) forward.