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Current Counter-Drone Technology Solutions to Shield Airports and Approach and Departure Corridors

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16. Abstract

The proliferation of drones has the potential to harm people and property. In particular, drones flying near airports and airport approaches can cause flight disruptions, as well as other serious challenges and incidents. There is a need to understand available technologies to protect Commonwealth of Massachusetts airport users and the traveling public. The objectives of this research were to accomplish both a literature search and a detailed synthesis of counter-drone technologies. The literature search has determined what technologies are currently available and are being pursued. Commercial off-the-shelf hardware that implements these technologies has been identified, and its costs and capabilities were described and assessed. On the basis of this research, recommendations were made regarding available counter-drone technologies, and a pilot program for the Massachusetts Department of Transportation Aeronautics Division to further explore counter-drone technologies has been proposed.

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Current Counter-Drone Technology Solutions to Shield Airports and Approach and Departure Corridors

Final Report

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Disclaimer

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Executive Summary

This study of Current Counter-Drone Technology Solutions to Shield Airports and Approach and Departure Corridors was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The proliferation of drones, or unmanned aerial systems (UASs), has the potential to harm people and property. In particular, drones flying near airports and airport approaches can cause flight disruptions, as well as other serious challenges and incidents. There is a need to understand available technologies to protect Commonwealth of Massachusetts airport users and the traveling public.

The objectives of this research were: (1) to accomplish a UAS-related literature survey and a review of commercially available counter-drone technologies; and (2) to develop recommendations for MassDOT regarding solutions to address the problem of noncooperative UASs in close proximity to airports. The literature search determined what technologies are currently available. The commercial off-the-shelf (COTS) hardware survey was performed in two stages. During the first stage, a survey of separate groups of stakeholders was performed in order to identify their opinions regarding the importance of different aspects of counter-UAS technologies, policies, and standards. The stakeholder survey helped the research team establish a basis for technology evaluation, performed at the next step. During the second step of the COTS survey, hardware that implements counter-UAS technology was identified, and its costs and capabilities were described and assessed.

The research team recommends that airports use multiple integrated technologies in a layered approach to detect, track, and interdict UASs. In addition, the team recommends that manufacturers be required to integrate geofencing into the GPS navigation systems of all commercially sold UASs over 0.55 lbs. Also, several counter-UAS systems are recommended for further investigation. Finally, the team recommends that a pilot program be implemented by the MassDOT Aeronautics Division to further explore counter-UAS technologies that have been proposed.

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List of Acronyms

Acronym	Expansion
ADS–B	Automatic dependent surveillance–broadcast
AUDS	Anti-UAV Defense System
COTS	Commercial-off-the-shelf
FAA	Federal Aviation Administration
GPS	Global positioning system
LiDAR	Light detection and ranging
MDR	Max detection range
MIR	Max interception range
N/D	No data
NextGen	Next Generation Air Transportation System
RF	Radio frequency
RFI	Request for Information
RGB	Red-green-blue
SIGINT	Signals intelligence
TBD	To be determined
TRID	Transportation Research International Documentation
UAS[*]	Unmanned aerial system
UAV[*]	Unmanned aerial vehicle

[*] The terms "UAS," "UAV," and "drone" are used interchangeably.

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1.0 Introduction

This study of Current Counter-Drone Technology Solutions to Shield Airports and Approach and Departure Corridors was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

The reduction in cost and innovations for global positioning systems (GPSs), cameras, and other advanced sensor-based technologies has led to an increase in the use of unmanned aerial vehicles (UAVs), also referred to as drones. The Federal Aviation Administration (FAA) has estimated that there could more than 2.5 million drones in the United States by 2020 that require registration *(1).* This proliferation of drones also has the potential to harm people and property. In particular, drones flying near airports and airport approaches can cause flight disruptions, as well as other serious challenges and incidents. There is a need to understand available technologies to protect Commonwealth airport users and the traveling public.

1.1 Problem Statement

As more and more unmanned aerial systems (UASs) are sold to commercial and recreational users, the risk that they will enter restricted areas and interfere with passenger flights rises. Between 2014 and 2015, the total number of undesirable encounters between UASs and manned aircrafts almost quadrupled and approached 1,000 in total. More than 300 of those can be defined as a “near-midair collision,” using FAA terminology, with other cases classified as observations reported by pilots or air traffic controllers *(2).*

This dramatic increase in the frequency of close encounters is alarming, as it makes the risk of a midair collision more likely in the near future. There have been several reasons why such encounters have become more and more common. The most obvious are:

- Lack of comprehensive laws on UAS operations
- Lack of proper education/training of UAS pilots
- Lack of strict enforcement
- Limited capabilities of modern UAS avionics and sensors
- Limited ground infrastructure to detect and track UASs
- Limited capabilities of manned aircraft sensors to detect and track UASs

1.2 Research Objectives

The objectives of this research were: (1) to accomplish a UAS-related literature survey and a review of commercially available counter-drone technologies; and (2) to develop recommendations for MassDOT regarding solutions to address problems related to noncooperative UASs in close proximity to airports. The literature survey was designed to determined what technologies are currently available and are being pursued. Commercial-off-the-shelf (COTS) hardware that implements these counter-drone technologies was identified, and its costs and capabilities were described and assessed.

1.3 Report Outline

The remainder of this report is organized as follows. Chapter 2 describes research methodology. Chapter 3 describes the results of the literature survey and the COTS survey. Chapter 4 provides conclusions and recommendations for implementation of counter-UAS technologies intended to protect airports and the traveling public. Chapter 5 provides a list of references. Chapter 6 contains appendices with detailed data collected during the literature and COTS surveys, as well as other reference material.

2.0 Research Methodology

The first task of this project was to survey both printed sources and Internet publications to determine what approaches were feasible and were being pursued. The initial result of this task was presented in the Literature Survey Report/Technology Digest.

The second task of this project was to evaluate the products that were identified in the first task. Three product categories were identified: ground-based drone detection, drone interception and interdiction (an action to divert, disrupt, or destroy non-cooperative UAS), and detection/interdiction combinations. The products were then grouped in one of these categories. For each category of products, attributes that reflect the cost and performance were determined. Each product was then evaluated based on a weighted sum of the product attributes.

The values for the weights were determined by using input from a technical evaluation team and the results of a survey of stakeholders, experts, and professionals within the UAS industry.

2.1 Literature Survey

The purpose of the literature survey was to collect preliminary information about technologies, trends, manufacturers, and products that can help to detect, track, and intercept noncooperative UASs in the proximity of airports. In addition, an effort was made to find information about the capabilities of collision avoidance equipment on board UASs. During the literature survey, the following categories of equipment with the potential to protect airports, their approaches, and the traveling public from UASs were identified:

- UAS onboard collision avoidance systems
- Ground-based UAS detection and tracking equipment
- UAS interception and control systems
- Detection and interdiction hybrid systems

The information was collected from professional literature, Internet publications, the Transportation Research International Documentation (TRID) database, conference proceedings, manufacturer brochures, and other sources.

Collected information was used to identify major problems and helped to prepare a set of questions for several stakeholder groups. In addition, established personal contacts with a wide group of key professionals from attended conferences created a basis for a core group of stakeholders for the COTS survey and helped to expedite Requests for Information (RFIs) to counter-UAS equipment manufacturers.

2.2 COTS Survey

The COTS survey consisted of two parts: a stakeholder survey, and a counter-UAS technology and product evaluation.

2.2.1. COTS Survey, Part One: Stakeholder Survey

The research team developed a short survey intended to obtain feedback from stakeholders, experts, and professionals within the UAS industry. The survey was conducted using SurveyMonkey. The link to the survey was sent via e-mail to 135 contacts. The prospective respondents for the survey were selected from the following sources:

- InterDrone 2016 professional contacts from Douglas Looze and Michael Plotnikov
- UTM 2016 professional contacts from Michael Plotnikov
- Professional contacts from Jeffrey DeCarlo
- Other professional contacts from Douglas Looze and Michael Plotnikov
- Professional contacts found via literature and Internet searches

Prospective survey respondents were grouped into seven categories:

- UAS Manufacturing or UAS Navigation and Collision Avoidance System Manufacturing
- Counter-UAS Equipment Manufacturing
- Research
- Law Practice
- Government
- Airport Operation
- Commercial UAS Operation

Each group was offered three to five UAS-related questions in their area of expertise (Appendix A in Section 6.1 lists the questions). Each question in the survey asked the respondent to rank his/her top three responses. The research team interpreted these rankings as the relative importance of the responses and applied weights to each answer accordingly. For each respondent's answer to each question, the highest-ranked response received a score of 3, while the lowest-ranked response received a score of 1. The team aggregated the scores within each of the categories, providing a total score for that category of responses. The team calculated the percentage of all scores for each category, and these percentages for each of the categories were used to compare the overall importance of each set of responses in the following sections. The outcome of the survey helped to identify the most important concerns related to noncooperative UAS incursions into a restricted airspace and provided hints for potential solutions to this problem. In addition, the results collected in this survey were used as a guide to establish a rating scale and to determine the initial weight for each of the counter-UAS systems parameters.

2.2.2. COTS Survey, Part Two: Counter-UAS Technology and Product Evaluation

The research team developed a short list of questions intended to collect information for counter-UAS equipment manufacturers about various parameters of their products. The Request for Information (RFI) was sent to 27 identified manufacturers. The counter-UAS manufacturers were selected from the following sources:

- Manufacturers that presented their product at the InterDrone 2016 Conference
- Manufacturers that presented their product at the UTM 2016 Conference
- Manufacturers found via literature and Internet searches

Manufacturers were grouped into three categories:

- Counter-UAS Detection and Tracking Equipment Manufacturers
- Counter-UAS Interdiction Equipment Manufacturers
- Counter-UAS Detection and Interdiction Hybrid Equipment Manufacturers

Each vendor received a set of questions regarding its product that was specific to its group (see Tables 2, 3, and 4 in Section 6.2, Appendix B).

The attributes for each group were divided by characteristics into three sets: performance, reliability, and cost. Each product received a weighted score for each attribute set. The weighted score for each set was determined by the following formula:

$$\boldsymbol{Total\ Score} = \left[\frac{(\boldsymbol{Attribute\ Value}) * (\boldsymbol{Weight})}{\mathbf{5} * (\boldsymbol{Sum\ of\ Weights})}\right] * \mathbf{100}$$

The term in the denominator and the multiplication by 100 were used to normalize the total score for each set, with 100 being the maximum total score.

A technical team was assembled to help determine the appropriateness of the attributes and weights. The technical team comprised a broad spectrum of individuals representing MassDOT, airport operators, federal and state agencies, aircraft operators, and independent engineers. The technical team is listed in Table 31 in Section 6.6, Appendix F.

The weights from the total-score computation were initially chosen by the research team using responses from the stakeholder survey as guidance. The initial weights and attributes were supplied to the technical team. Based on feedback from the technical team, it was decided that:

- Each of the three characteristic sets should be scored separately.
- Risk and cost attributes should be investigated in detail for a few desirable products.
- A few additional attributes relating to human factors and risk should be added.

The final values for the scale bins and weights for the performance attributes are shown in Table 30 in Section 6.5, Appendix E.

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3.0 Results

3.1 Literature Survey Results

From the results of the literature survey, the research team identified 33 different products from 31 manufacturers. The products were identified in the following categories:

- UAS Collision Avoidance: 6 products
- UAS Detection and Tracking Systems: 9 products
- UAS Interception and Control Systems: 8 products
- UAS Detection and Interdiction Hybrid Systems: 10 products

Literature survey results in each category are discussed in Subsections 3.1.1 to 3.1.4.

3.1.1. UAS Onboard Avionics and Sensor Equipment

One of the popular solutions is internal programming of onboard avionics to incorporate geofencing of flight-restricted areas. Many UAS manufacturers, including the market leader, DJI, integrate this solution into their products. While relatively inexpensive and fairly easy to implement, this approach cannot help in situations where there is a navigation equipment malfunction on board a UAS, or in cases of intentional malicious modifications to UAS firmware. In addition, geofencing does not help to avoid potentially dangerous encounters between UASs and other aircrafts and structures outside of restricted areas.

Onboard sensors can significantly reduce potentially dangerous situations created by UASs. However, there are many challenges associated with development of effective collision avoidance systems for UASs. Key challenges include the following:

- Price
- Form factor and weight
- Robustness
- Range and field-of-view
- Resolution
- Impact of weather conditions
- Impact of dynamic environments
- Sensor data processing requirements

There are a number of obstacle detection/collision avoidance technologies available to be installed on UASs. On a high level, sensing technologies can be divided into passive, such as visual or acoustic sensors, and active, which include both emitter and receiver to measure distance to surrounding objects. Generally, active detection systems provide superior performance as compared to passive detection systems. Passive sensors tend to be less expensive, lighter, and do not require as much operating power as do active sensors. A brief description of active detection technologies is provided in Table 5 (see Section 6.3, Appendix C).

As can be observed from Table 5, the best solution would be to use multiple active sensors with different detection technologies for collision avoidance. In reality, however, there are serious cost, weight, power, and data processing constraints that make such design impossible at the current level of technology development. As a result, a combination of passive and active sensors is often implemented as a compromise solution.

Finally, it is important to keep in mind that available onboard sensors in real-world situations will only be capable of preventing collisions between UASs and static objects, like structures, or slow-flying aircrafts, such as balloons or helicopters, as their detection range rarely exceeds 200 feet. Consequently, UAS ability to avoid collision with fast-moving aircraft may be limited *(3).* However, as relatively light radars with effective range of about one mile are under development, new generations of UASs are expected to have improved capabilities in collision avoidance *(4).*

3.1.2. Ground-based UAS Detection and Tracking Equipment

The ground-based UAS detection and tracking technology solutions are similar to those designed to be installed on UASs. Active detection methods could be generally classified as radio, sound, and light-based. Passive detection methods utilize optical, sound, and radio-frequency (RF) sensors.

Unlike devices mounted on board the UAS, ground-based sensor systems are typically much more powerful and robust, due to fewer constraints related to size, weight, power consumption, and data processing requirements. As a result, there are several ground-based passive detection and tracking systems that have proved to be very effective to detect and track UASs at both long (RF-spectrum scanning) and medium-to-short distances (acoustic) *(5, 6).* A brief summary of selected ground-based UAS passive detection systems is presented in Table 6 (see Section 6.3, Appendix C).

There are some challenges, too. The biggest challenge is that UASs represent a very small target often moving at a low altitude and are usually made of composite materials that decrease the probability of stable detection. Also, small UASs do not carry a transponder such as the one used in automatic dependent surveillance–broadcast (ADS–B) systems proposed in the Next Generation Air Transportation System (NextGen) for aircrafts operated in controlled airspace *(7, 8, 9).*

As a result, to achieve reliable detection and tracking of UASs, most COTS systems integrate several types of detectors, both active and passive. Examples of such comprehensive solutions are those currently offered by Gryphon Sensors (Skylight, ACR Hawk) and by Dedrone (DroneTracker Multi-Sensor). The smaller DroneTracker system offers a range of UAS detection and tracking of up to 1,640 feet (500 meters), while the largest Gryphon Skylight claims capability to detect UASs as far away as 8.5 kilometers with radar and up to 3 kilometers with its spectrum sensing (S2) and slew-to-cue camera *(10, 11).*

Another notable example of a complex ground-based UAS detection and tracking system is offered by DeTect, Inc. The DroneWatcher and the HARRIER Drone Surveillance Radar provide a comprehensive, layered solution available for detection, tracking, alerting, and interdiction of DJI Phantom-size UASs at distances up to 4 kilometers. Advanced technology combines signals intelligence (SIGINT) and radar for detection and tracking *(12).* All systems listed in this section also integrate and control third-party devices, including signal jammers, to intercept intruder UASs. A brief summary of selected ground-based UAS active/passive detection systems is presented in Table 7 (see Section 6.3, Appendix C).

3.1.3. UAS Interception and Interdiction Systems

Currently, many different methods have been considered to deter, immobilize, or destroy invasive UASs in drone-restricted areas. A variety of solutions include the following *(13)*:

- RF signal jamming (can be either wide area or targeted)
- UAS firmware hacking
- Flight disruption by use of physical means (destructive or nondestructive)
- Use of trained predator birds

The first method, RF signal jamming, utilizes two different approaches. The first approach uses a broad-spectrum, wide-area signal jamming. The second approach uses narrow beam/narrow RF spectrum antennae to disrupt a drone's operation and safely bring it down to the ground.

The second method, UAS firmware hacking, is somewhat similar to the first one, but instead of targeting a radio communication between the UAS and its pilot/controller, it targets internal program code by injecting into the code a command for immediate landing as the UAS enters a restricted area.

The third method, flight disruption by physical means, implements physical objects to bring down invasive UASs, either without destruction (such as Drone SkyWall, a net and parachute combination) or destructive (such as use of guns or weapons).

The last method, use of predator birds, is somewhat exotic but has proven to be a well-working solution. In the Netherlands, law enforcement has been training bald eagles to see drones as prey and hunt them down *(14).* Table 8 provides a brief summary of the advantages and drawbacks of various drone deterrence and interception methods (see Section 6.3, Appendix C).

3.1.4. UAS Tracking and Interdiction Hybrid Systems

While most ground-based UAS detection and tracking equipment manufacturers do not provide a UAS interception and control system as a part of their package, there is a clear demand for such all-in-one systems due to increasing awareness about threats presented by noncooperative UASs to airports and other restricted areas. As a result, several vendors, such as Dedrone, integrate COTS interception systems offered by different vendors *(10),* while others, such as Liteye/Blighter, offer a comprehensive anti-UAS defense system (AUDS) that integrates the electronic scanning air security radar, stabilized electro-optic detector, infrared and daylight cameras, target-tracking software, and a directional radio frequency inhibitor to detect, track, classify, disrupt, and defeat UASs at ranges of up to several kilometers *(15, 16).*

3.2 Stakeholder Survey Results

As of the date of submission, the team received 51 responses. Of these, 13 surveys were discarded as incomplete, and 38 were considered for the analysis. Table 1 provides an example of a rating calculation based on collected survey responses.

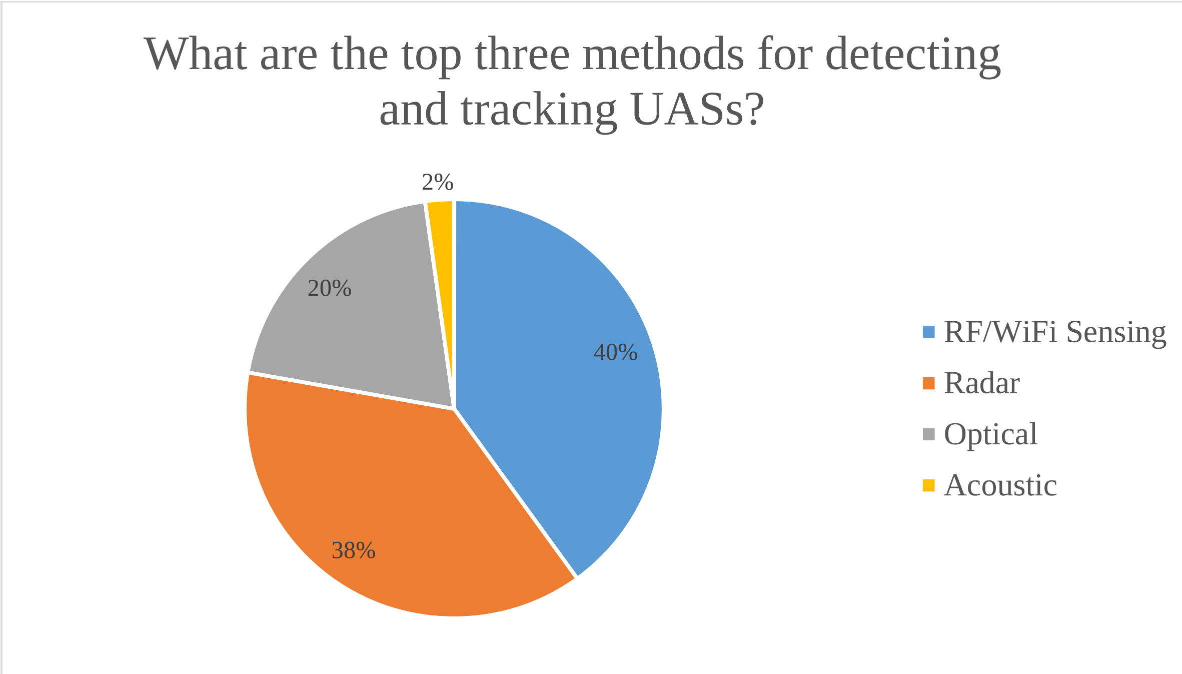
Table 1: Example of a rating calculation based on collected survey responses

What are the top three methods for detecting and tracking UASs?	A	B	C	D	E	F	G	H	I	J	TOTAL	PERCENTAGE
RF/Wi-Fi Sensing	1	2			1	3	2	3	3	3	18	40%
Radar	3	3			3	2	3	1		2	17	38%
Optical	2	1			2			2	2		9	20%
Acoustic						1					1	2%

The question in this example, “What are the top three methods for detecting and tracking UASs?” is the third question that was posed to counter-UAS technology manufacturers, 10 of whom responded and who are labeled “A” through “J.” Note that respondents “C” and “D” responded to some of the questions in the survey but abstained from this particular question, so their scores are absent here.

The outcomes of the survey are presented in graphic form for better visualization of the observed trends. Examples of the graphic representation of the results of the conducted survey are presented in Figure 1. Responses on other survey questions, in both graphic and tabular forms, are presented in Section 6.4, Appendix D.

Figure 1: Survey results: Methods for UAS interdiction as ranked by the stakeholders



On the basis of the results obtained during the stakeholder survey, the research team presents the following conclusions:

- Stakeholders are most concerned about the following major threats associated with UASs operated in close proximity to airports:
  - Collision with aircraft (36%)
  - Airport systems disruption (21%)
  - Poor communication with UAS pilots (12%)

- Counter-UAS manufacturers envision the following technologies to be the most effective to detect and track UASs near airports:
  - Radar (38%)
  - RF (38%)
  - Optical (23%)

- Counter-UAS manufacturers expect that the following technologies can be the most effective to intercept and interdict noncooperative UASs near airports:
  - RF signal jamming or spoofing (53%)
  - Electromagnetic (13%)
  - Kinetic (13%)

- Airport operators report that the top three most desirable methods for mitigating the threat of UASs are:
  - Geofencing/no-fly zone enforcement (47%)
  - Detection and interdiction systems (33%)
  - Education, registration, or training regulations (13%)

Another notable result of the survey is that different groups of stakeholders look at the problem of UAS operations near airports from different angles. For example, counter-UAS manufacturers consider inadequate regulations, specifically radio system operation or jamming regulations, to be the greatest obstacle to developing effective counter-UAS technologies (45%). On the other hand, government officials, lawyers, and researchers acknowledge policy and education as the single most-important factor to safeguard airports from UASs (20%), while also acknowledging the high importance of radio-frequency jamming and spoofing technologies (19%).

A complete summary of the stakeholder survey results is presented in Section 6.4, Appendix D.

3.3 COTS Technology Evaluation Results

The research team contacted 25 manufacturers with the RFI regarding 27 different anti-UAS products. A full list of the counter-UAS products, their manufacturers, and the corresponding product category is given in Table 29 in Section 6.5, Appendix E. The products were identified as belonging to the following categories:

- UAS Detection and Tracking Systems: 9 products
- UAS Interception and Control Systems: 8 products
- UAS Detection and Interdiction Hybrid Systems: 10 products

At the time of publication of this report, a total of 21 responses have been received. Of these, 16 provided attribute information (shown in light gray in Table 29), and 5 declined to participate (shown in light red in Table 29). Another 5 manufacturers declined to provide information because the data produced by the system is classified, or requested that the team sign a nondisclosure agreement. The latter systems were not pursued due to time constraints.

Incomplete RFI data was supplemented with information from available public sources, such as brochures, web publications, and reports from previous similar studies *(17).* The products with available data were evaluated on the basis of the methodology presented in Section 2.2.1. Detailed results of the counter-UAS equipment evaluation are presented in Section 6.7, Appendix G.

In the UAS Detection and Tracking category, the following systems are recommended for further investigation:

- DroneWatcher by DeTect
- Skylight by Gryphon Sensors

- SATS2 by Adsys Controls

In the UAS Interdiction category, no systems that were available for analysis are recommended for further consideration at airports.

In the UAS Detection and Interdiction Hybrid category, the following systems are recommended for further investigation:

- Counter UAV System by Airbus
- ARDRONIS-I by R&S
- AUDS by Liteye

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4.0 Conclusions and Recommendations

The research team makes the following conclusions and recommendations.

4.1 Stakeholder Survey Conclusions and Recommendations

On the basis of the results of the stakeholder survey, the research team makes the following conclusions and recommendations:

- Collision of noncooperative UASs with commercial aircrafts is a major concern.
- Geofencing is considered to be the most effective method to keep the majority of UASs away from restricted areas, such as airports.
- Radar and radio signal intelligence are considered the most effective UAS detection and tracking technologies.
- Radio and GPS signal jamming are considered the most effective UAS interception and interdiction solutions.
- Adapting laws and regulations to permit radio-frequency jamming or spoofing on systems that demonstrate safe and effective use of these technologies would be beneficial.

4.2 COTS Survey Conclusions and Recommendations

On the basis of the results of the COTS survey, the research team makes the following conclusions and recommendations:

- It is recommended that airports use multiple integrated technologies in a layered approach to detect and track UASs.
- It is recommended that airports use multiple integrated technologies in a layered approach to interdict UASs.
- It is recommended that MassDOT support federal legislation that requires all commercially sold UASs over 0.55 lbs. to integrate geofencing into their GPS navigation systems.
- It is recommended that MassDOT create a pilot program to perform further evaluation of selected counter-UAS products.

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6.0 Appendices

6.1 Appendix A: Stakeholder Survey Questions

The following are the questions that were asked of survey participants. The survey was designed in such a manner that each respondent needed to answer both the “opening questions” and “closing questions,” as well as questions associated with the group they most closely identified with. The groups include the following: Counter-UAS Manufacturer, Government, Law, Research, UAS Manufacturer, UAS Operator, and Airport Operator.

Opening Questions

1. Please provide us with a way to identify you.

2. Which one of the following groups most closely matches the organization that you represent? If there is more than one group, you will have the opportunity to select another one later in the survey.

Counter-UAS Manufacturer Questions

1. What are the top three technical challenges to detecting and tracking UASs? Please rank your responses such that “Challenge 1” is the greatest, and “Challenge 3” is the least.

2. What are the top three technical challenges to interdiction of UASs? Please rank your responses such that “Challenge 1” is the greatest, and “Challenge 3” is the least.

3. What are the top three methods for detecting and tracking UASs? Please rank your responses such that “Method 1” is the most effective, and “Method 3” is the least effective.

4. What are the top three methods for interdiction of UASs? Please rank your responses such that “Method 1” is the most effective, and “Method 3” is the least effective.

Government, Law, or Researcher Questions

1. What are the top three concerns for safeguarding airports from UASs? Please rank your responses such that “Concern 1” is the greatest concern, and “Concern 3” is the least concern.

2. What are the top three methods for safeguarding airports from UASs? Please rank your responses such that “Method 1” is the most effective, and “Method 3” is the least effective.

3. What are the top three legal challenges to implementing UAS interdiction technologies? Please rank your responses such that “Challenge 1” is the greatest, and “Challenge 3” is the least.

UAS Manufacturer Questions

1. What are the top three technologies to place on UASs to prevent collision with aircraft? Please rank your responses such that “Technology 1” is the most effective, and “Technology 3” is the least effective.

2. What are the top three technical challenges to implementing these technologies on UASs to prevent collision with aircraft? Please rank your responses such that “Challenge 1” is the greatest, and “Challenge 3” is the least.

3. What are the top three technologies to place on UASs to prevent entry into airport airspace? Please rank your responses such that “Technology 1” is the most effective, and “Technology 3” is the least effective.

4. What are the top three technical challenges to implementing these technologies on UASs to prevent entry into airport airspace? Please rank your responses such that “Challenge 1” is the greatest, and “Challenge 3” is the least.

UAS Operator Questions

1. In the course of your day-to-day operations, what are your top three concerns with flying UASs close to restricted areas? Please rank your responses such that “Concern 1” is the greatest, and “Concern 3” is the least.

2. How effective is the FAA’s small UAS regulatory framework as outlined in CFR 14 Part 107? Please respond by adjusting the slider below. Please provide any comments below.

3. How supportive would you be of a motion to make geofencing mandatory for all commercial UASs and UAS operations? Please respond by adjusting the slider below. Please provide any comments below.

Airport Operator Questions

1. What are the top three concerns for safeguarding airports from UASs? Please rank your responses such that “Concern 1” is the greatest, and “Concern 3” is the least.

2. What are the top three methods for safeguarding airports from UASs? Please rank your responses such that “Method 1” is the most effective, and “Method 3” is the least effective.

3. What are the top three challenges to implementing UAS tracking and interdiction technologies at airports? Please rank your responses such that "Challenge 1" is the greatest, and "Challenge 3" is the least.

4. When implementing counter-UAS technologies to safeguard airports, is it more important to guard particular sections of the airports, such as final approach corridors, or is it equally important to secure all airspace around an airport up to a 5-mile radius in all directions? What should be the balance of priority? Please respond by adjusting the slider below. Please provide any comments below.

5. In your opinion, what technology or equipment would need to be implemented on a UAS and on the ground in order to allow safe UAS operations within your airport's airspace?

Closing Questions

1. Thank you for answering the survey questions! At the beginning of the survey, you had to select one group from a list that most accurately described your organization. The groups listed were: UAS Manufacturing or UAS Navigation and Collision; Avoidance System Manufacturing; Counter-UAS Equipment Manufacturing; Research; Law Practice; Government Airport Operation; or Commercial UAS Operation. Is there a second group from that list that matches your organization? If so, would you be able to answer a few more questions intended for members of that group?

2. What is the second group that best matches the organization you represent?

Thank you for your responses; your input is greatly appreciated! If you have any additional comments, you may write them in the box below. You may return to a question to change your answers, or click "DONE" to finish and submit your response.

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6.2 Appendix B: Counter-UAS Equipment Evaluation Parameters

Table 2: Drone detection system parameters

Parameter	Parameter Description
Capital Cost	The initial cost of the system. This includes production, shipment, and installation costs.
Operational Cost	The annual maintenance cost for all system components.
Training Cost	The cost to train system operators.
Deployment Time	The time period (in days) from when an order for a system is placed to when it is deployed and operational on a site.
Expected Lifetime	The expected lifetime (in years) of successful operation before the system fails to function correctly.
Max Wind Tolerance	The maximum wind gusts (in mph) the system can tolerate and remain operational.
Max Operating Temperature	The maximum temperature (in Fahrenheit) the system can tolerate and remain operational.
Min Operating Temperature	The minimum temperature (in Fahrenheit) the system can tolerate and remain operational.
Field of View (Detection)	The arc (in degrees) within which the system can detect and track a UAS.
Max Detection Range (MDR)	The maximum detection range (in km) of a DJI Phantom-sized UAS as reported by the manufacturer.
Detection Probability	Detection probability of a DJI Phantom-sized UAS at MDR as reported by the manufacturer.
False Positives	The probability of the system reporting a false positive for a DJI Phantom-sized UAS at MDR.
Location Tracking Accuracy	Location tracking accuracy of a DJI Phantom-sized UAS at MDR as reported by the manufacturer.
Sensor Array	Detection method:[†] acoustic (0.5), RGB visual (1.5), thermal visual (1), LiDAR (1), radar (2.5), passive RF (2)
Weight	The total weight of the system in kg.

[†] Numbers in parentheses indicate points a system was awarded for including a specific type of sensor.

Table 3: Drone interdiction system parameters

Parameter	Parameter Description
Capital Cost	The initial cost of the system. This includes production, shipment, and installation costs.
Operational Cost	The annual maintenance cost for all system components.
Training Cost	The cost to train system operators.
Deployment Time	The time period (in days) from when an order for a system is placed to when it is deployed and operational on a site.
Expected Lifetime	The expected lifetime (in years) of successful operation before the system fails to function correctly.
Max Wind Tolerance	The maximum wind gusts (in mph) the system can tolerate and remain operational.
Max Operating Temperature	The maximum temperature (in Fahrenheit) the system can tolerate and remain operational.
Min Operating Temperature	The minimum temperature (in Fahrenheit) the system can tolerate and remain operational.
Max Intercept Range (MIR)	The maximum range (in km) of intercepting a DJI Phantom-sized UAS as reported by the manufacturer.
Field of View (Intercept)	The horizontal arc (in degrees) within which the system can engage a UAS.
Compatibility	Does the system meet minimum standards for compatibility? (Y/N)
UAS Speed Limits	The maximum speed (in mph) at which the system can successfully intercept a DJI Phantom-sized UAS.
UAS Weight Limits	The maximum weight (in kilograms) of a UAS that can be successfully intercepted by the system.
Intercept Probability	The probability of intercepting a DJI Phantom-sized UAS moving at 35 mph at MIR.
Response Time	The time to intercept a UAS after it has been detected.
Intercept Technology	Interdiction method:[‡] RF jamming (4), spoofing/hacking (3), netting (2), directed energy (2.5), birds (1)
Weight	The total weight of the system in kilograms.

[‡] Numbers in parentheses indicate points for implementing a specific method of interdiction in the system.

Table 4: Drone detection/interdiction hybrid system parameters

Parameter	Parameter Description
Capital Cost	The initial cost of the system. This includes production, shipment, and installation costs.
Operational Cost	The annual maintenance cost for all system components.
Training Cost	The cost to train system operators.
Deployment Time	The time period (in days) from when an order for a system is placed to when it is deployed and operational on a site.
Expected Lifetime	The expected lifetime (in years) of successful operation before the system fails to function correctly.
Max Wind Tolerance	The maximum wind gusts (in mph) the system can tolerate and remain operational.
Max Operating Temperature	The maximum temperature (in Fahrenheit) the system can tolerate and remain operational.
Min Operating Temperature	The minimum temperature (in Fahrenheit) the system can tolerate and remain operational.
Field of View (Detection)	The arc (in degrees) within which the system can detect and track a UAS.
Max Detection Range (MDR)	The maximum detection range (in km) of a DJI Phantom-sized UAS as reported by the manufacturer.
Detection Probability	Detection probability of a DJI Phantom-sized UAS at MDR as reported by the manufacturer.
False Positives	The probability of the system reporting a false positive for a DJI Phantom-sized UAS at MDR.
Location Tracking Accuracy	Location tracking accuracy of a DJI Phantom-sized UAS at MDR as reported by the manufacturer.
Max Intercept Range (MIR)	The maximum range (in km) of intercepting a DJI Phantom-sized UAS as reported by the manufacturer.
Field of View (Intercept)	The horizontal arc (in degrees) within which the system can engage a UAS.
Compatibility	Does the system meet minimum standards for compatibility? (Y/N)

Table 4 (cont.): Drone detection/interdiction hybrid system parameters

Parameter	Parameter Description
UAS Speed Limits	The maximum speed (in mph) at which the system can successfully intercept a DJI Phantom-sized UAS.
UAS Weight Limits	The maximum weight (in kilograms) of a UAS that can be successfully intercepted by the system.
Intercept Probability	The probability of intercepting a DJI Phantom-sized UAS moving at 35 mph at MIR.
Response Time	The time to intercept a UAS after it has been detected.
Sensor Array	The types of sensors in the system[§]: acoustic (0.5), passive RGB visual (1.5), passive thermal visual (1), LiDAR (1), radar (2.5), passive RF (2)
Intercept Technology	Interception method:[§] RF jamming (4), spoofing/hacking (3), netting (2), directed energy (2.5), birds (1)
Weight	The total weight of the system in kilograms.

[§] Numbers in parentheses indicate points for including a specific type of sensor or implementing or a method of interdiction in the system.

6.3 Appendix C: Literature Survey

Table 5: Onboard active obstacle detection/collision avoidance systems for UASs

Type of Sensor	Radio	Sound	Light
Technology Example	Radar/microwave	Sonar/ultrasound	LiDAR/LED, laser
Advantages	•Rugged, mature technology •Can see through certain obstacles •High tolerance to weather conditions	•Low cost •Small size, easy to integrate	•Low sensitivity to material type •Easier beam forming •More versatile on shorter distance •High resolution
Drawbacks	•Potential for radio frequency interference	•Slow detection response •May be adversely affected by weather conditions	•Affected by weather conditions •Performance affected by elements such as condensation, frost, dirt, or dust
Commercially Available Products	Echodyne MESA-DAA (in development)	Intel RealSense & Yuneec (camera + ultrasound); SenseFly Albris	Velodyne Puck LITE; Leddar by LeddarTech

Table 6: Ground-based UAS passive detection systems

Manufacturer/System	Dedrone DroneTracker Multi-Sensor	DroneShield	AARonia A.G. Real-Time RF Drone and Radar Detection System	Sensofusion Airfence
Type of Sensor(s)	Passive acoustic, ultrasonic, visual, RGB + NIR, RF, Wi-Fi	Passive acoustic, omni-directional and directional long range	Spectrum sensing	Spectrum sensing
Sensor Range	500 m	1 km (long range) 100 m (omni-directional)	1 km (omni-directional)	10 km (omni-directional)
Weight (kg)	37	20	41	N/D

Table 7: Ground-based UAS active/passive detection systems

Manufacturer/System	Gryphon Sensors ACR Hawk	DeTect Drone Watcher/HARRIER	Gryphon Sensors Skylight	Blighter Anti-UAV Defense System (AUDS)
Type of Sensor(s)	Pulse-Doppler radar, slew-to-cue camera	Pulse-Doppler radar, spectrum sensing (SIGINT)	Pulse-Doppler radar, spectrum sensing (S2), slew-to-cue camera	Pulse-Doppler radar, stabilized electro-optic director, IR and RGB cameras, directional RF inhibitor
Sensor Range	5 km—radar 3 km—camera	3.8 km	8.5 km—radar 3 km—S2 and camera	Up to 10 km
Weight (kg)	34	182	182	N/D

Table 8: Brief summary of drone deterrence and interception methods

Method	Signal Jamming		Program Hacking	Physical		Birds of Prey
	Wide Beam	Narrow Beam		Non-destructive	Destructive	
Advantages	• Large coverage • Easily implemented	• No or minimal side effect	• Wide area of coverage	• No interference • Safer	• No interference • Higher success rate	• Low cost • Natural predator
Drawbacks	• RF interference • Legality • High power required • Some UAS immune	• May be labor intensive • More expensive • Some UAS immune	• Interception of all types of intruder UASs is not guaranteed	• Labor intensive • Expensive • Short effective range	• Expensive • Legality	• Limited to smaller UAS only • Labor intensive
Example	• Dedrone/HP Wuest Gmbh Jammer	• Battelle DroneDefender	• N/A in U.S. market	• OpenWorks SkyWall	• Firearms, EMP, Laser	• N/A in US market

6.4 Appendix D: Stakeholder Survey Data

Appendix D contains tables and corresponding pie charts that provide summaries of responses of stakeholder survey respondents. Each response to the question is weighted by the importance assigned to it (the first response was weighted 3, the second response was weighted 2, and the third response was weighted 1). The percentages shown in each pie chart reflect the weighted total share of each response, as displayed in each preceding table.

6.4.1. UAS Manufacturing or UAS Navigation and Collision Avoidance System Manufacturing (Number of Respondents: 4)

Table 9: UAS onboard collision avoidance technologies rating

What are the top three technologies to place on UASs to prevent collision with aircraft?	A	B	C	D	TOTAL	PERCENTAGE
ADS–B	3	1	2		6	25%
Optical Sensors	1	3		3	7	29%
Geofencing			3		3	13%
Radar	2		1	2	5	21%
LATAS LTE		2			2	8%
Acoustic				1	1	4%

Figure 2: UAS onboard collision avoidance technologies rating

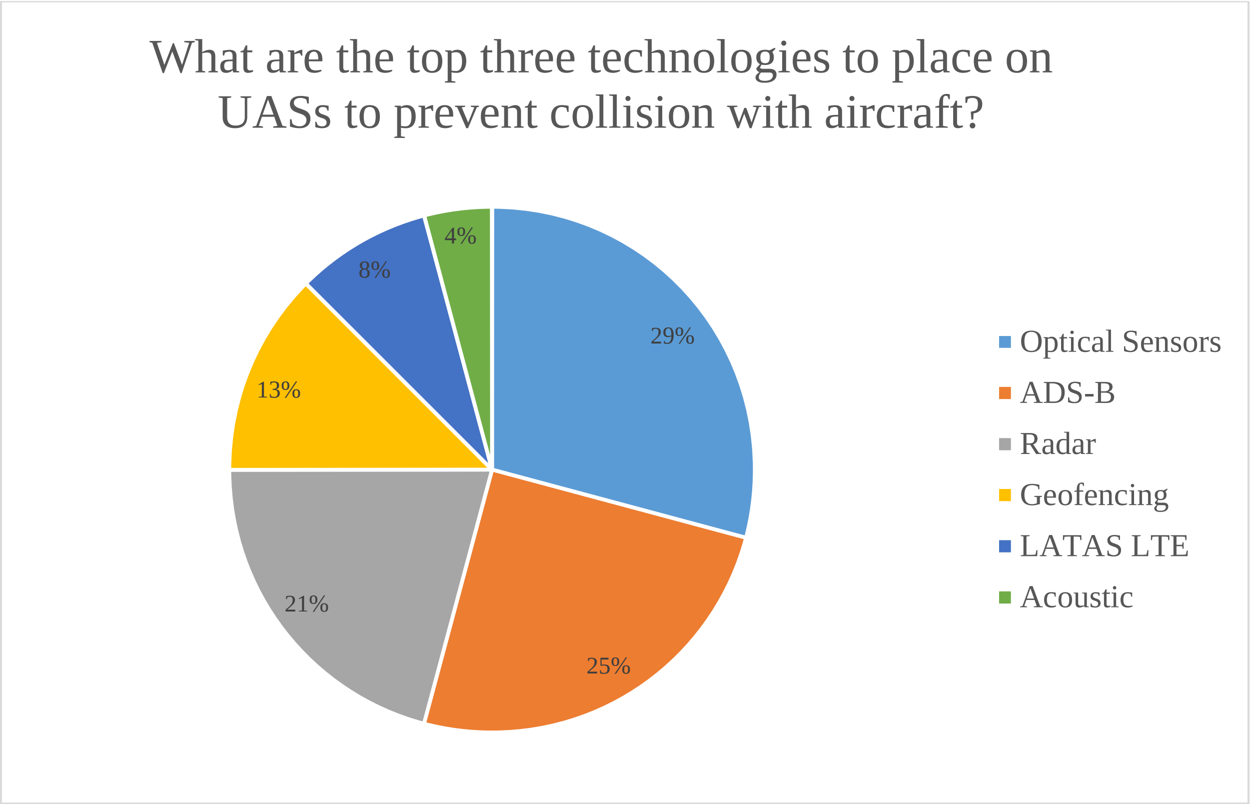


Table 10: Technical challenges to implement collision avoidance technologies

What are the top three technical challenges to implementing these technologies on UASs to prevent collision with aircraft?	A	B	C	TOTAL	PERCENTAGE
Cost	2	3		5	42%
Immature Technology	3			3	25%
Connectivity		2		2	17%
Weight	1	1		2	17%

Figure 3: Technical challenges to implement collision avoidance technologies

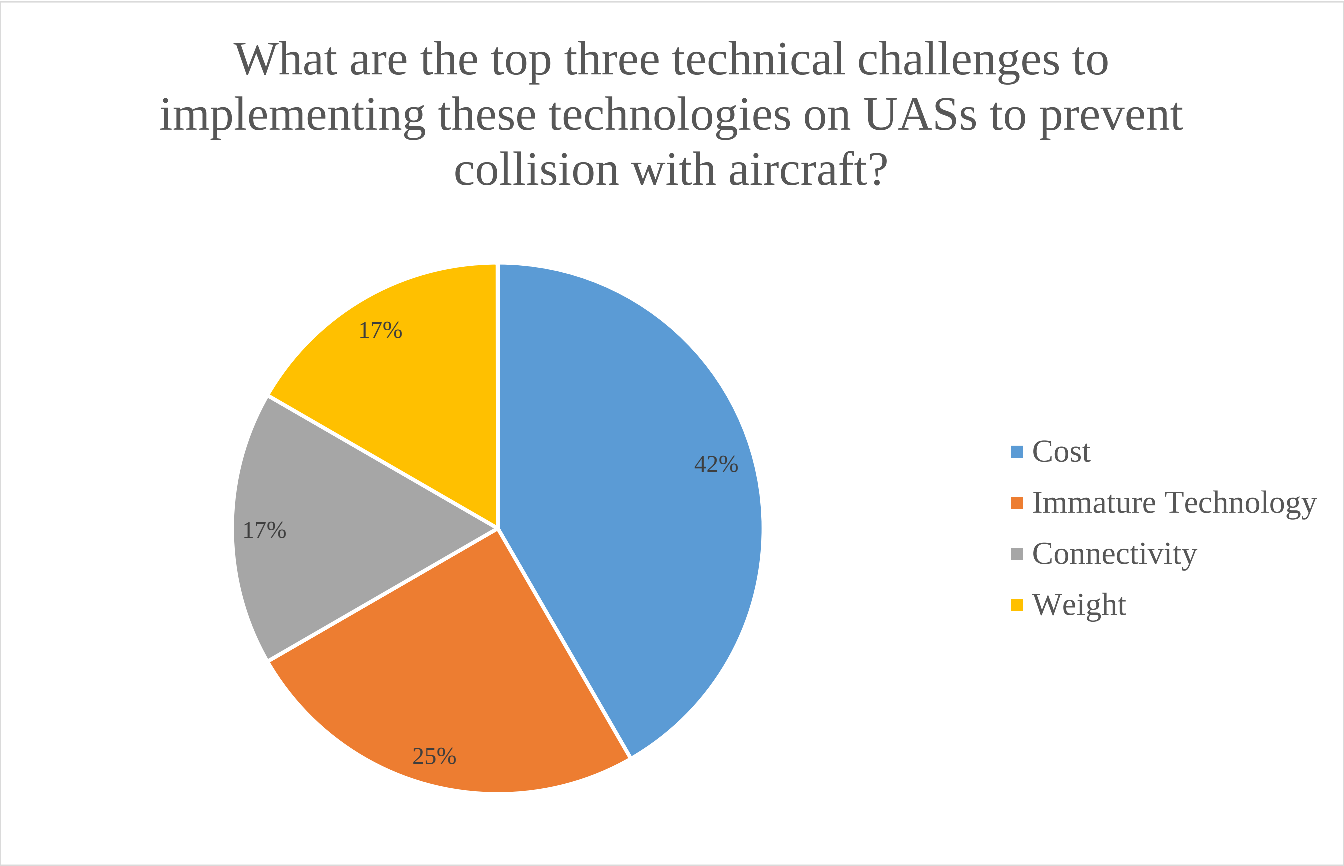


Table 11: Onboard technologies to prevent UASs from entering into a restricted airspace

What are the top three technologies to place on UASs to prevent entry into airport airspace?	A	B	C	TOTAL	PERCENTAGE
Geofencing	3	2		5	63%
Pilot Awareness (Tech)		3		3	38%

Figure 4: Onboard technologies to prevent UASs from entering into a restricted airspace

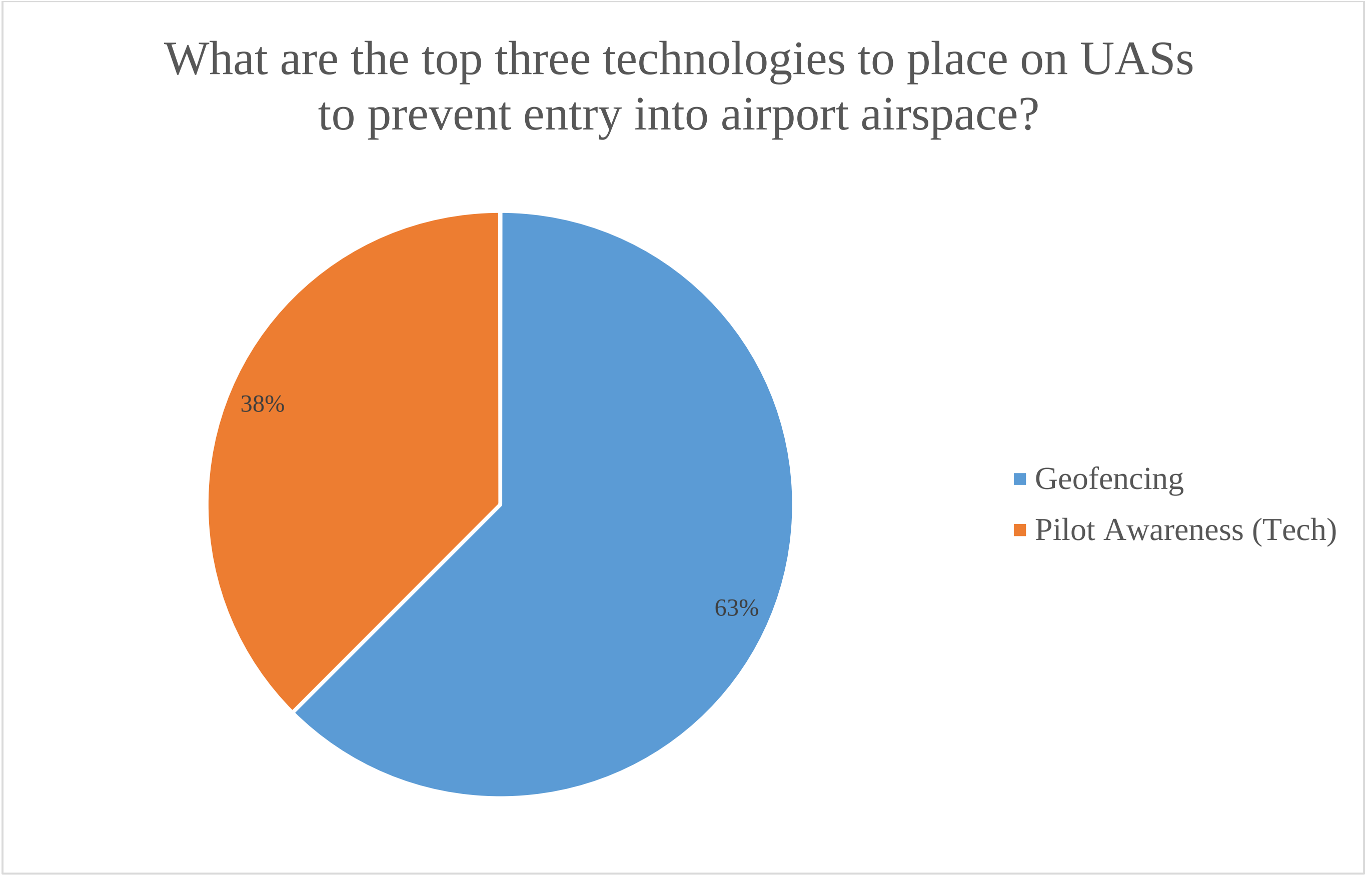
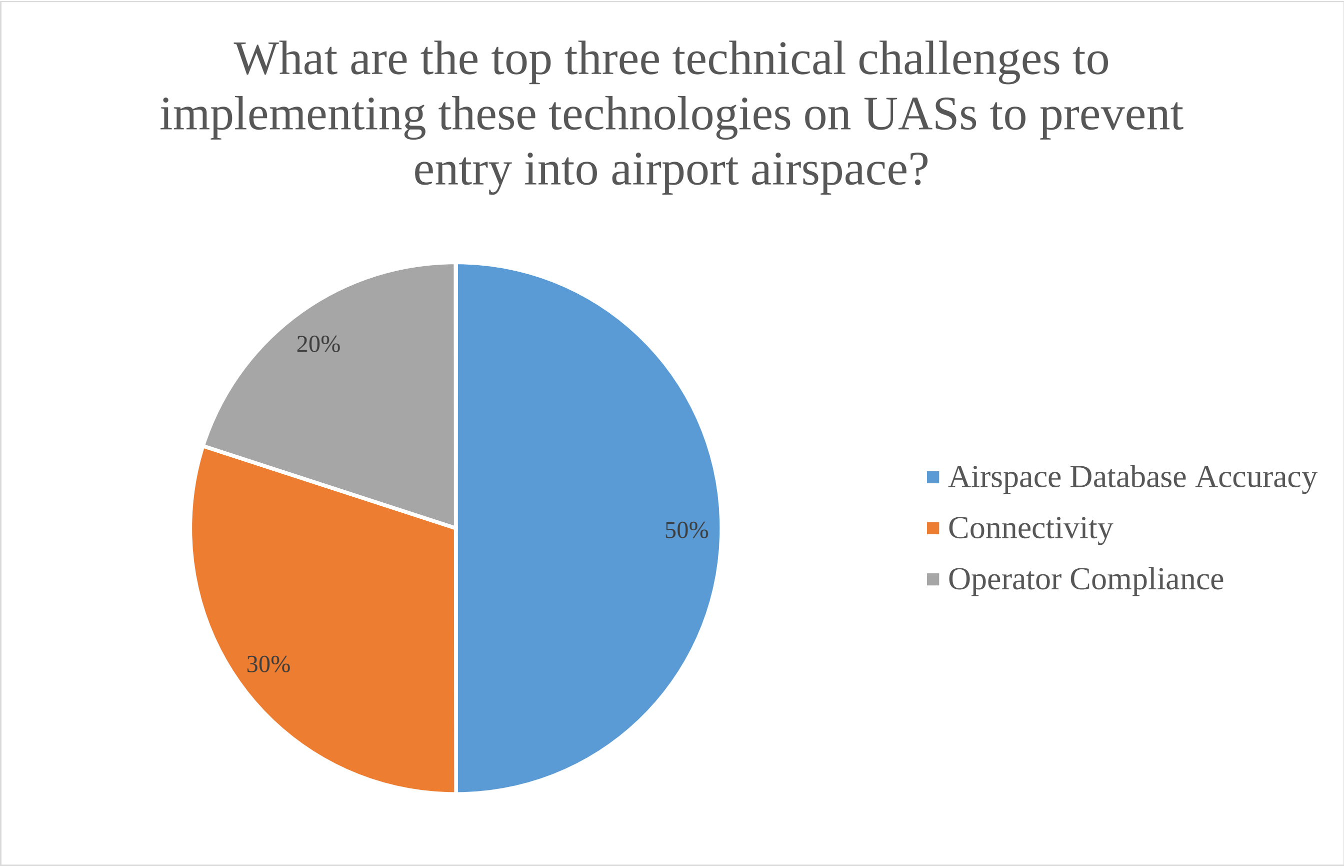


Table 12: Challenges to implement technologies to prevent UAS entry into a restricted airspace

What are the top three technical challenges to implementing these technologies on UASs to prevent entry into airport airspace?	A	B	C	TOTAL	PERCENTAGE
Airspace Database Accuracy	3	2		5	50%
Connectivity		3		3	30%
Operator Compliance	2			2	20%

Figure 5: Challenges to implement technologies to prevent UAS entry into a restricted airspace



Counter-UAS Equipment Manufacturing
(Number of Respondents: 10)

Table 13: Technical challenges to detect and track UASs

What are the top three technical challenges to detecting and tracking UASs?	A	B	C	D	E	F	G	H	I	J	TOTAL	PERCENTAGE
Unique/Novel UASs (e.g., DIY UASs), Speed of Advancement	3							3	2	3	11	28%
Classifying UASs (vs. Others)		3					3				6	15%
Pilot Location Accuracy	2								3		5	13%
FCC Regulations			3			1					4	10%
Range Effectiveness		2					2				4	10%
GPS Hopping						3					3	8%
Encrypted Data						2					2	5%
Computing Constraints for Signal Analysis										2	2	5%
UAS Location Accuracy							1				1	3%
Weather									1		1	3%

Figure 6: Technical challenges to detect and track UASs

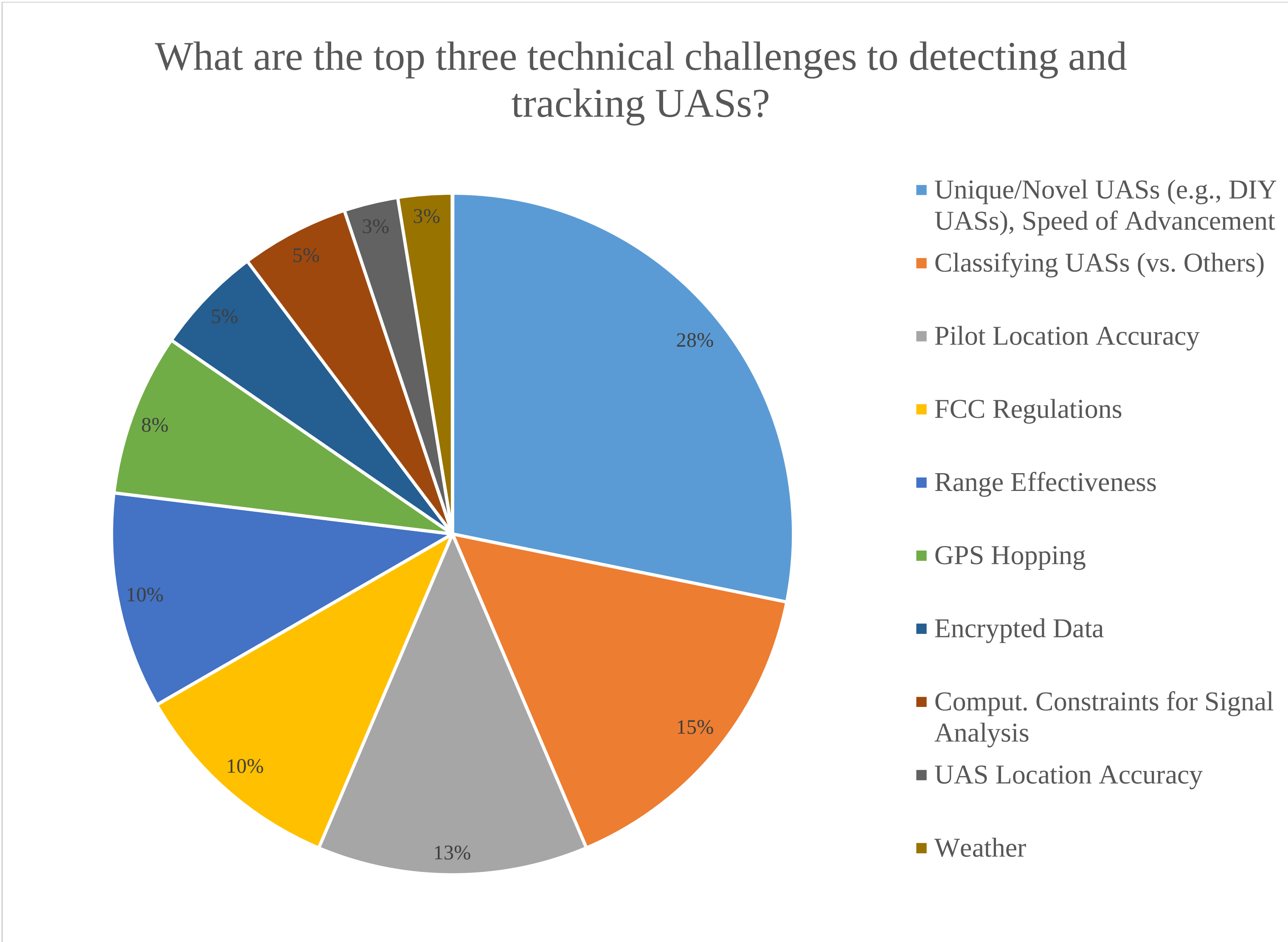


Table 14: Technical challenges for UAS interdiction

What are the top three technical challenges to interdiction of UASs?	A	B	C	D	E	F	G	H	I	J	TOTAL	PERCENTAGE
Regulation (e.g. FCC)		3			3	1	3		3	2	15	44%
Collateral Damage Mitigation		2					2				4	12%
Unique/Novel UASs								1		3	4	12%
GPS Hopping						3					3	9%
Detection of UAS Target								3			3	9%
Encrypted RF						2					2	6%
Autonomous UASs (Operation w/ no RF signal)								2			2	6%
Multiple Target Engagement		1									1	3%

Figure 7: Technical challenges for UAS interdiction

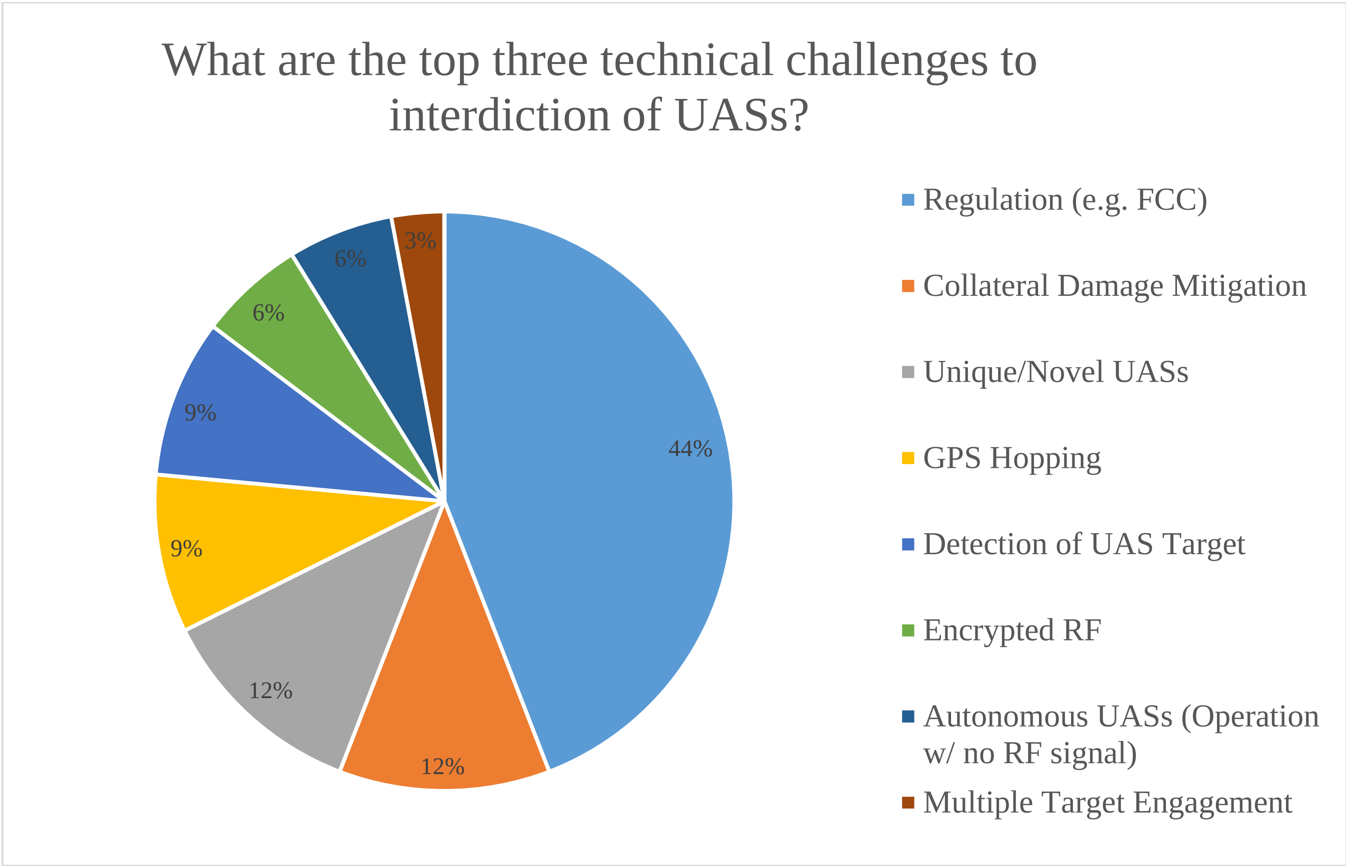


Table 15: The best technologies to detect and track UASs

What are the top three methods for detecting and tracking UASs?	A	B	C	D	E	F	G	H	I	J	TOTAL	PERCENTAGE
RF/Wi-Fi Sensing	1	2			1	3	2	3	3	3	18	40%
Radar	3	3			3	2	3	1		2	17	38%
Optical	2	1			2			2	2		9	20%
Acoustic						1					1	2%

Figure 8: The best technologies to detect and track UASs

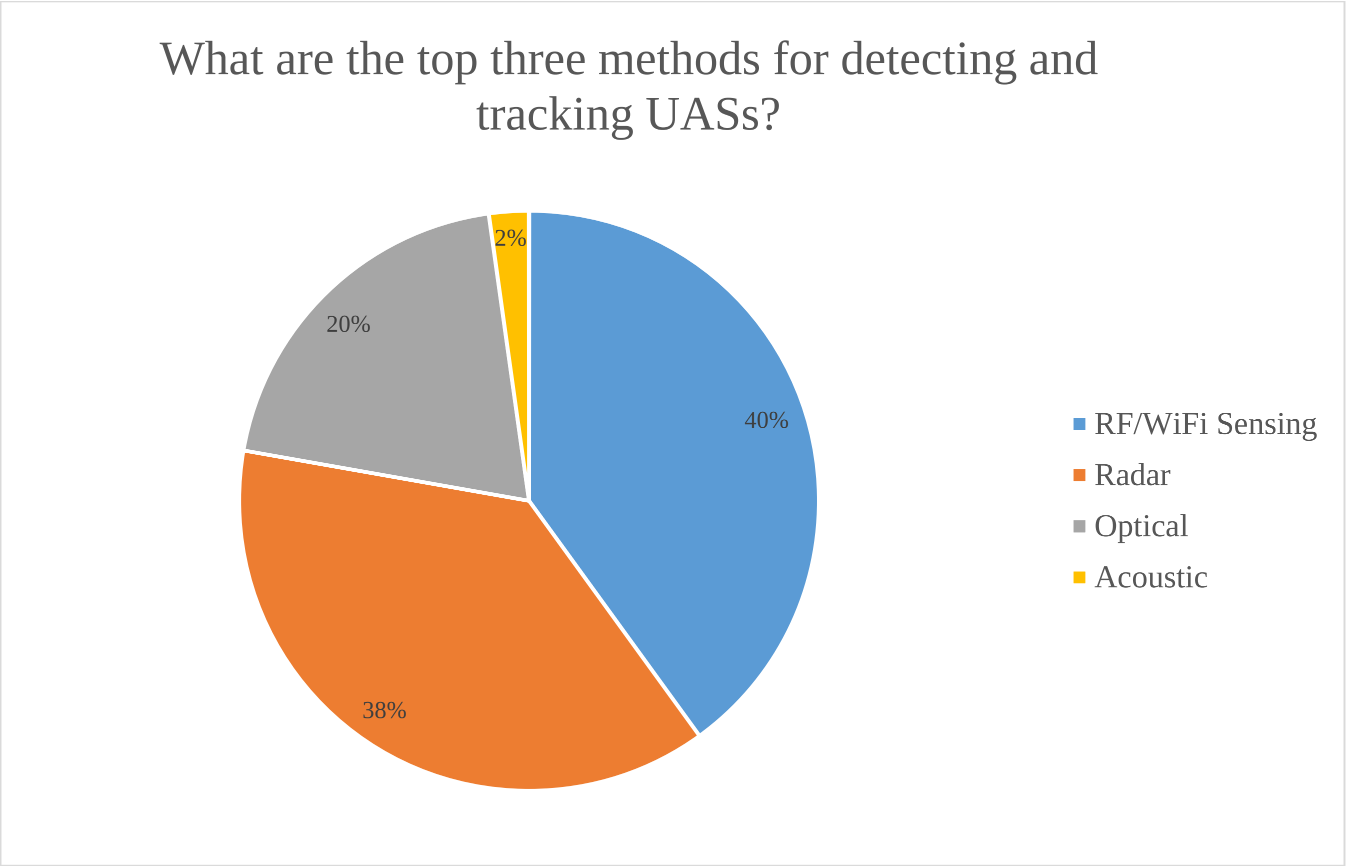
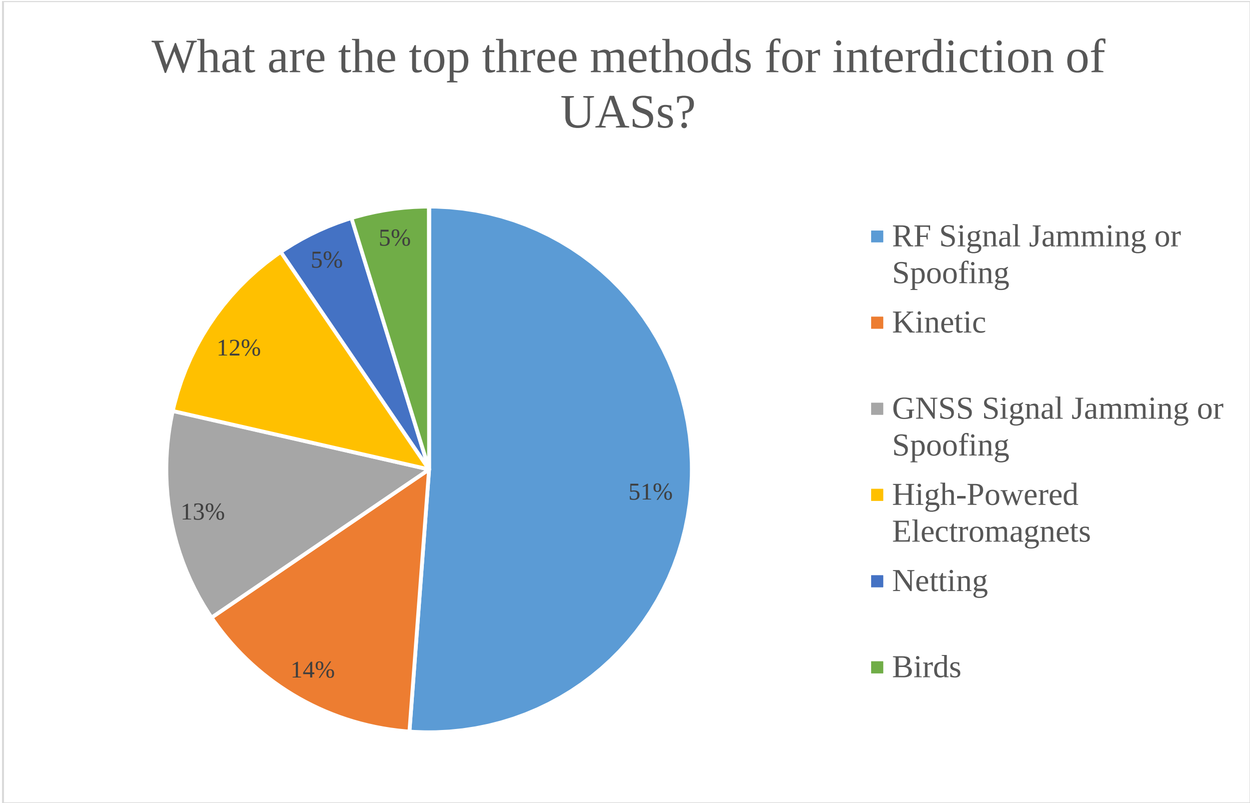


Table 16: The best methods for UAS interdiction

What are the top three methods for interdiction of UASs?	A	B	C	D	E	F	G	H	I	J	TOTAL	PERCENTAGE
RF Signal Jamming or Spoofing	3	3			3	3	2	3	3	1.5	21.5	51%
Kinetic	2				1			2		1	6	14%
GNSS Signal Jamming or Spoofing					2	2				1.5	5.5	13%
High-Powered Electromagnets		2					3				5	12%
Netting						1	1				2	5%
Birds		1						1			2	5%

Figure 9: The best methods for UAS interdiction



Research, Law Practice, and Government
(Number of Respondents: 14)

Table 17: Major concerns regarding UASs near airports

What are the top three concerns for safeguarding airports from UASs?	A	B	C	D	E	F	G	H	I	J	K	L	M	N	TOTAL	PERCENTAGE
Aircraft Collision	3	3	3	3	3	2		3				3			23	34%
Hobbyist DIY UASs, Negligence, or Lack of Coordination			2	2	2		2		1.5						9.5	14%
(Need for) Technical Capabilities		2					1				3			2	8	12%
Nefarious UAS Actors				1			3	2	1.5						7.5	11%
Communication or Airport System Disruption												2	2	3	7	10%
Regulation			1										3		4	6%
Airport Personnel Safety										3					3	4%
Infrastructure Damage						1				2					3	4%
Economic Damage/ Loss of Business										1		1			2	3%

Figure 10: Major concerns regarding UASs near airports

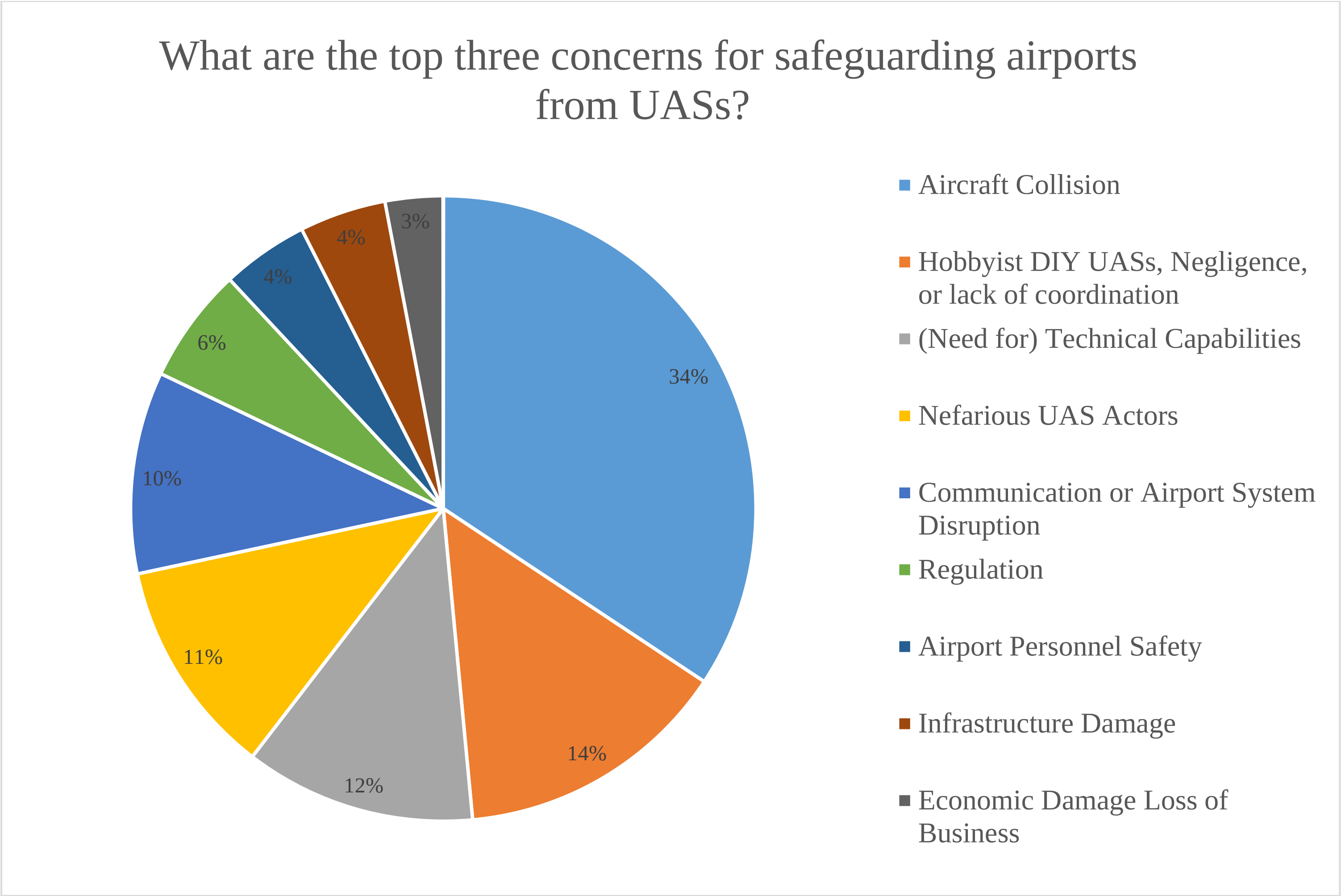


Table 18: The best methods to safeguard airports from UASs

What are the top three methods for safeguarding airports from UASs?	A	B	C	D	E	F	G	H	I	J	K	L	M	N	TOTAL	PERCENTAGE
Regulation of Public Policy or Education	3	3	2	3		3				1					15	20%
Radar Detection		1		1			3	3		3			3		14	19%
RF Jamming or Spoofing	1				3	2		1	2			2		3	14	19%
Other Detection Methods (e.g., RF, Optical, Active Location Reporting)	1	1		2				2		2		1	3		12	16%
Kinetic/Physical Interdiction	1				2	1	2		3					2	11	15%
Geofencing			3		1				1			3			8	11%
Birds														1	1	1%

Figure 11: The best methods to safeguard airports from UASs

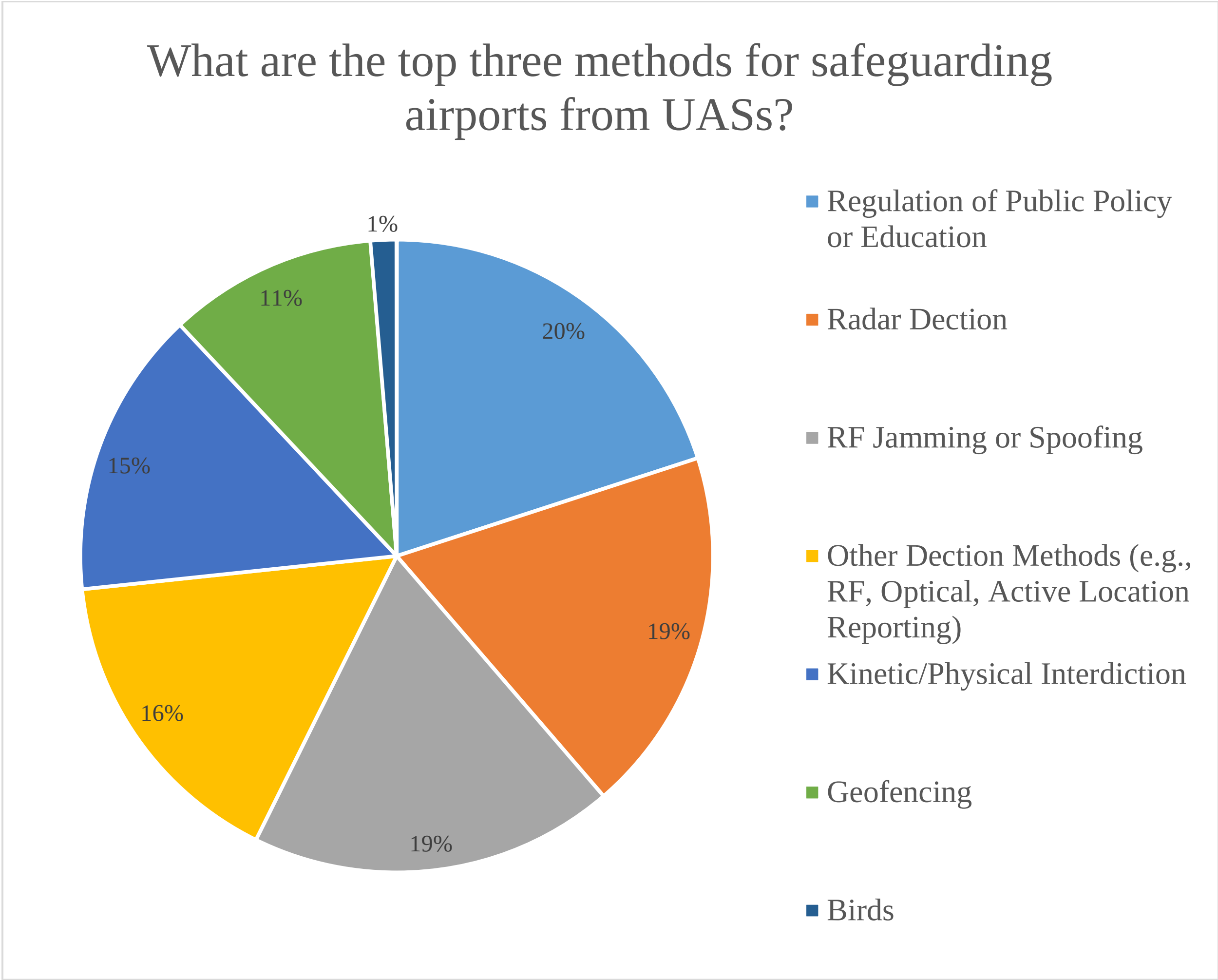
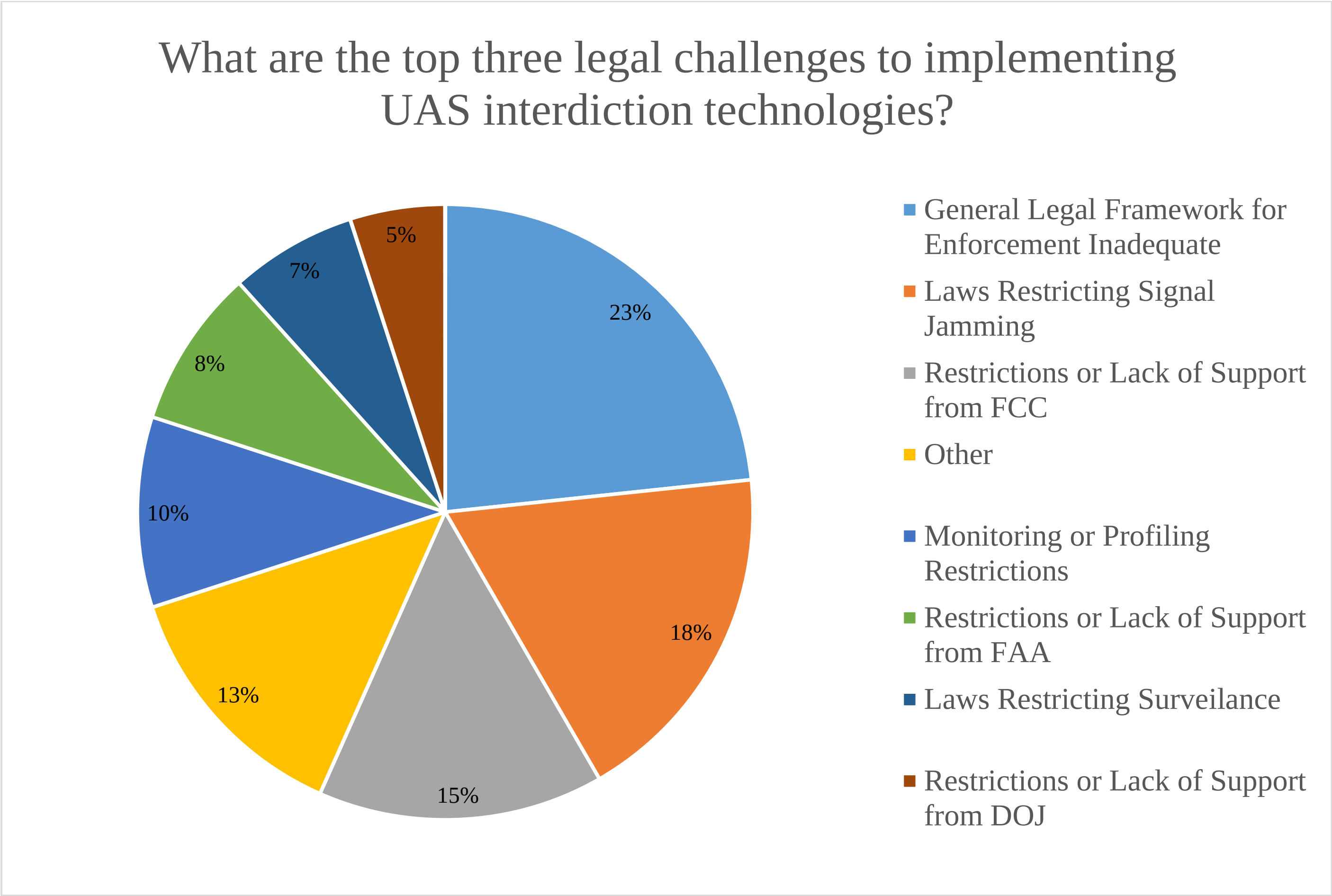


Table 19: Legal challenges to implement UAS interdiction systems

What are the top three legal challenges to implementing UAS interdiction technologies?	A	B	C	D	E	F	G	H	I	J	K	L	M	N	TOTAL	PERCENTAGE
Legal Framework for Enforcement Inadequate			3		3	2				3	3				14	23%
Laws Restricting Signal Jamming				2		3	3						3		11	18%
Restrictions or Lack of Support from FCC		3						3				3			9	15%
Other	3		2	1	2										8	13%
Monitoring or Profiling Restrictions				3					3						6	10%
Restrictions or Lack of Support from FAA		1						2				2			5	8%
Laws Restricting Surveillance							2		2						4	7%
Restrictions or Lack of Support from DOJ		2										1			3	5%

Figure 12: Legal challenges to implement UAS interdiction systems



Airport Operation
(Number of Respondents: 6)

Table 20: Major concerns regarding UASs near airports

What are the top three concerns for safeguarding airports from UASs?	A	B	C	D	E	F	TOTAL	PERCENTAGE
General Disruption Caused by Proximate UAS	3	2	1	3	1	3	13	38%
Aircraft Collision		3	3		3		9	26%
Privacy/Security from UAS Imaging Around Airport				1		2	3	9%
Terrorist Activity		1	2				3	9%
Frequency Conflicts					2		2	6%
Separation Issues of Depart/Approach Path				2			2	6%
Communication with UAS Pilots and Other Operations	2						2	6%

Figure 13: Major concerns regarding UASs near airports

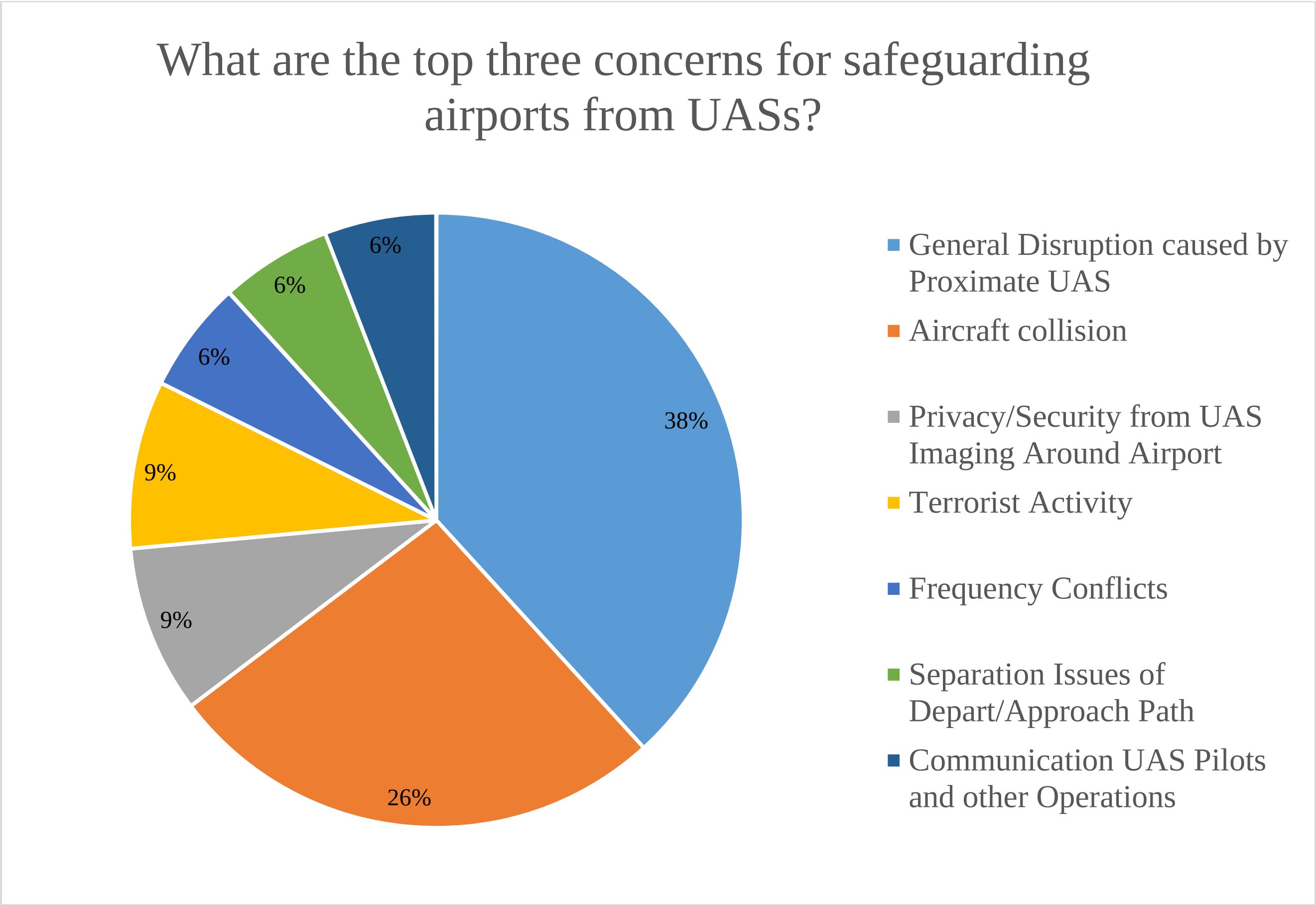


Table 21: Top methods to safeguard airports from UASs

What are the top three methods for safeguarding airports from UASs?	A	B	C	D	E	F	TOTAL	PERCENTAGE
Geofencing/No-Fly Zone Enforcement	3		3	3	2	3	14	47%
Detection and Interdiction Systems	2	3			3	2	10	33%
Education, Registration, or Training Regulations		2	2				4	13%
UAS Operator–Airport Operator Communication					1	1	2	7%

Figure 14: Top methods to safeguard airports from UAS

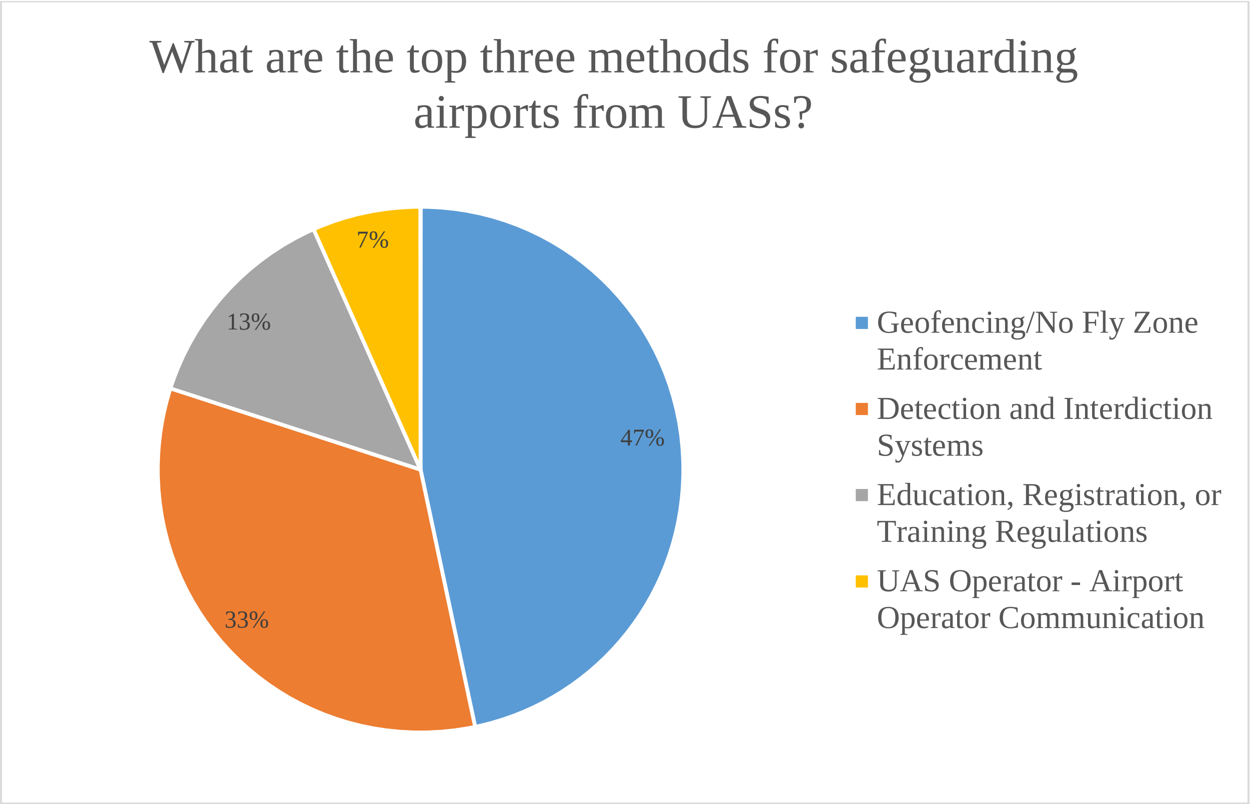


Table 22: Major challenges to implement UAS tracking and interdiction at airports

What are the top three challenges to implementing UAS tracking and interdiction technologies at airports?	A	B	C	D	E	F	TOTAL	PERCENTAGE
Need for Standardization of Technology or Ability to Understand/Operate Technology	1	2	3	3		2	11	34%
Funding/Cost	3	1	2		2	1	9	28%
More Reliable Technology Needed	2	3					5	16%
Insufficient Regulations					1	3	4	13%
UAS Operator Cooperation					3		3	9%

Figure 15: Major challenges to implement UAS tracking and interdiction at airports

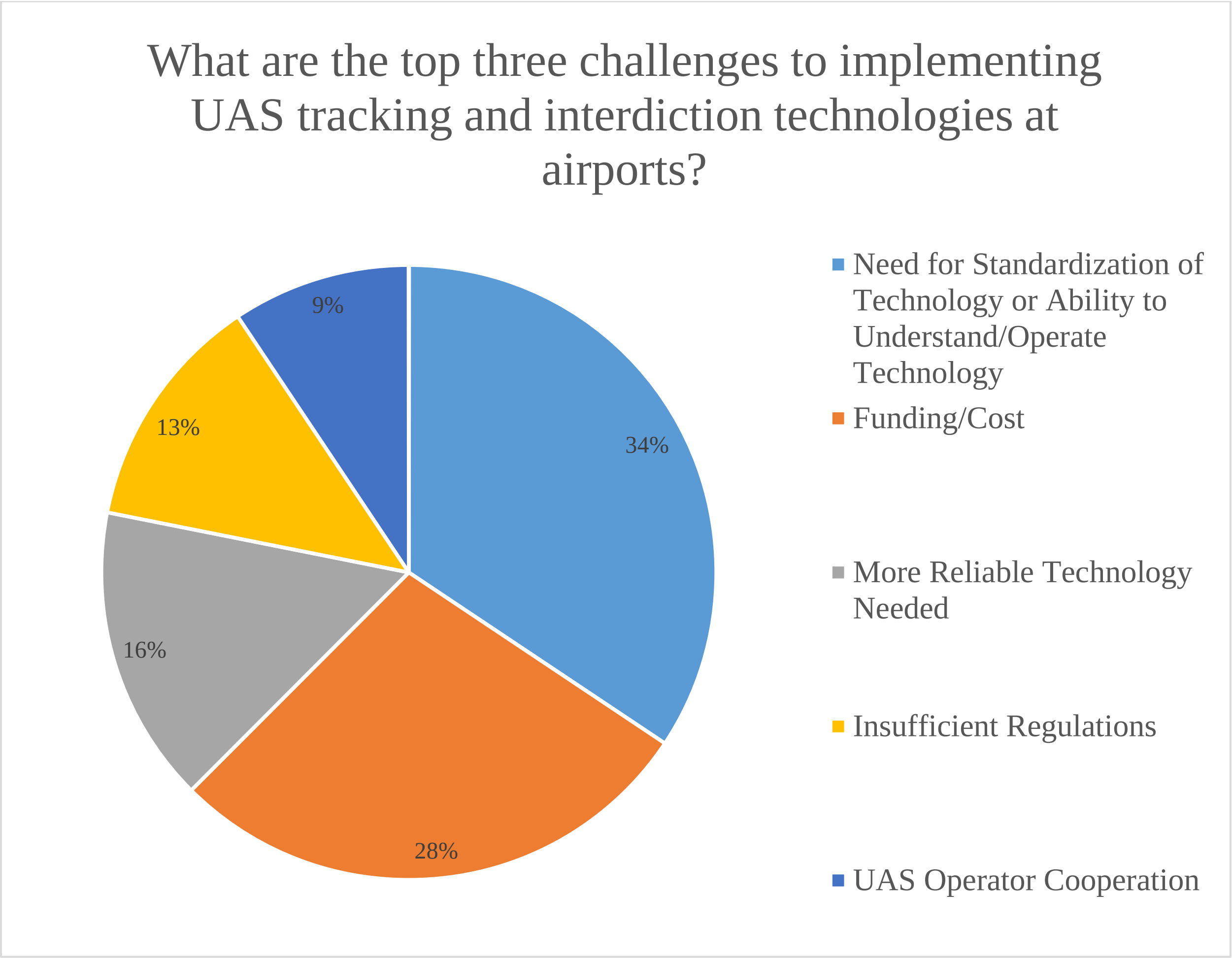


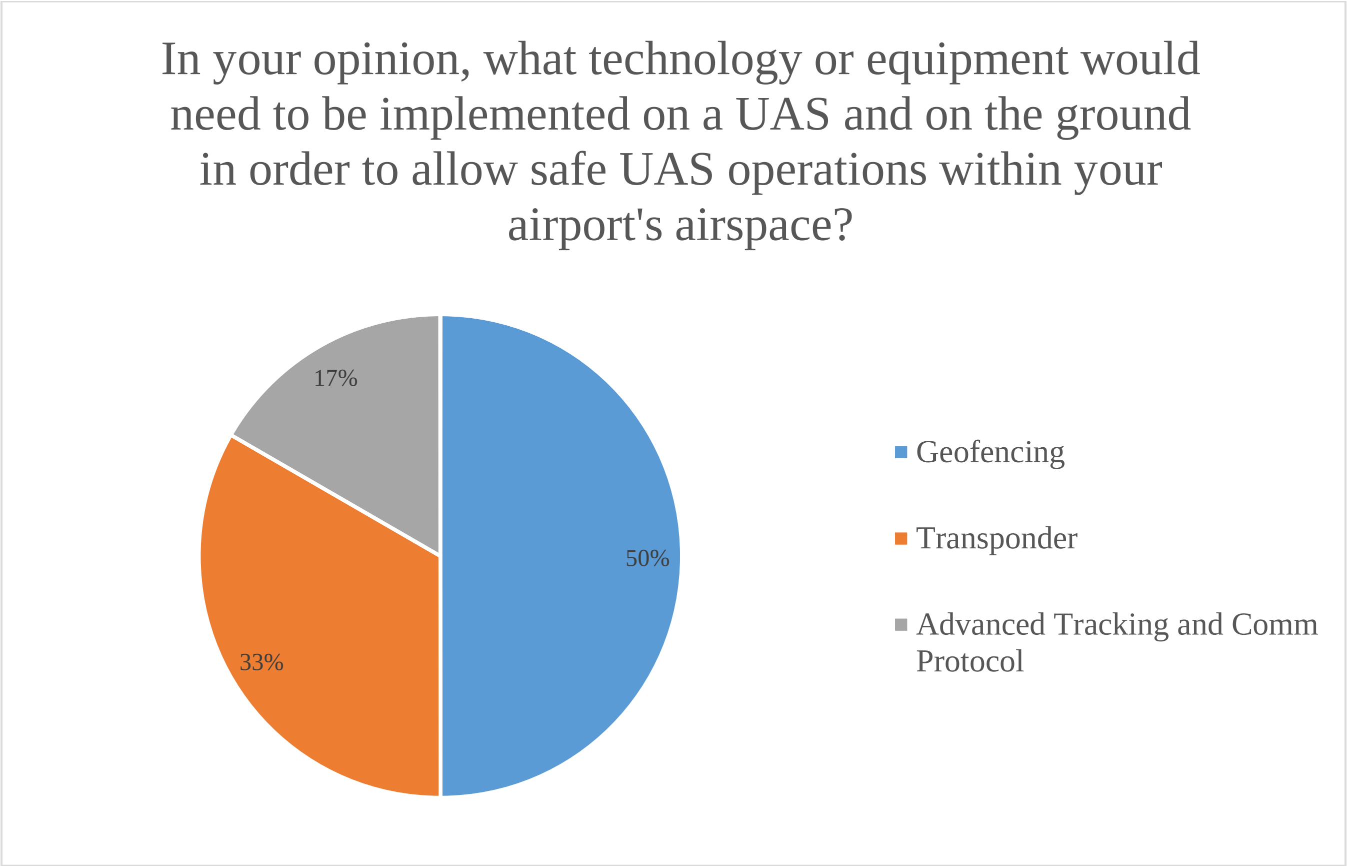
Table 23: Priority of protection from UASs at airports: entire area vs. corridors

When implementing counter-UAS technologies to safeguard airports, is it more important to guard particular sections of the airports, such as final approach corridors, or is it equally important to secure all airspace around an airport up to a 5-mile radius in all directions? What should be the balance of priority? (1: Just Approach and Departure Corridors) – (10: All areas are equally essential)	A	B	C	D	E	F	TOTAL	Average
Score	5	4	5	5	7	5	31	5.17

Table 24: Technical equipment that may allow safe UAS operations in airports

In your opinion, what technology or equipment would need to be implemented on a UAS and on the ground in order to allow safe UAS operations within your airport's airspace?	A	B	C	D	E	F	TOTAL	PERCENTAGE
Geofencing	1			1	1		3	50%
Transponder			1			1	2	33%
Advanced Tracking and Comm Protocol		1					1	17%

Figure 16: Technical equipment that may allow safe UAS operations in airports



UAS Commercial Operators
(Number of Respondents: 4)

Table 25: Major concerns regarding UAS operations near airports

What are the top three concerns for safeguarding airports from UASs?	A	B	C	D	TOTAL	PERCENTAGE
Collision with Aircraft	1		3		4	22%
Adherence to FAA Regulations	3				3	17%
Knowledge of UAS Location				3	3	17%
Communication with Other Entities	2				2	11%
Safety of Non-Participants			2		2	11%
Negligence of Other Actors				2	2	11%
General Risk			1		1	6%
Equipment Failure				1	1	6%

Figure 17: Major concerns regarding UAS operations near airports

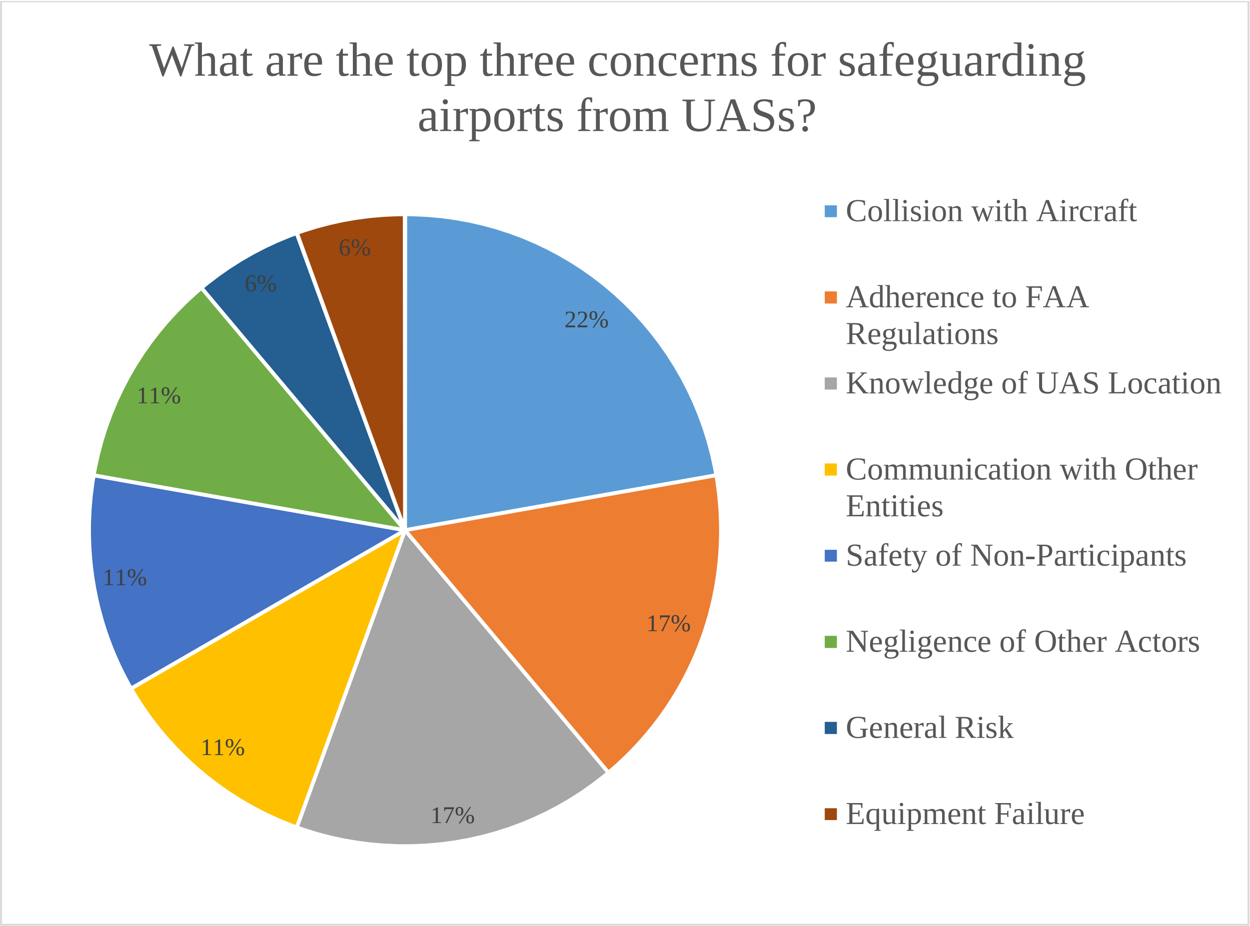


Table 26: Perception of CFR 14 Part 107 effectiveness

How effective is the FAA's small UAS regulatory framework as outlined in CFR 14 Part 107?	A	B	C	D	AVERAGE
Score	4	8	2	8	5.5

Table 27: Acceptance of mandatory geofencing for all commercial UASs

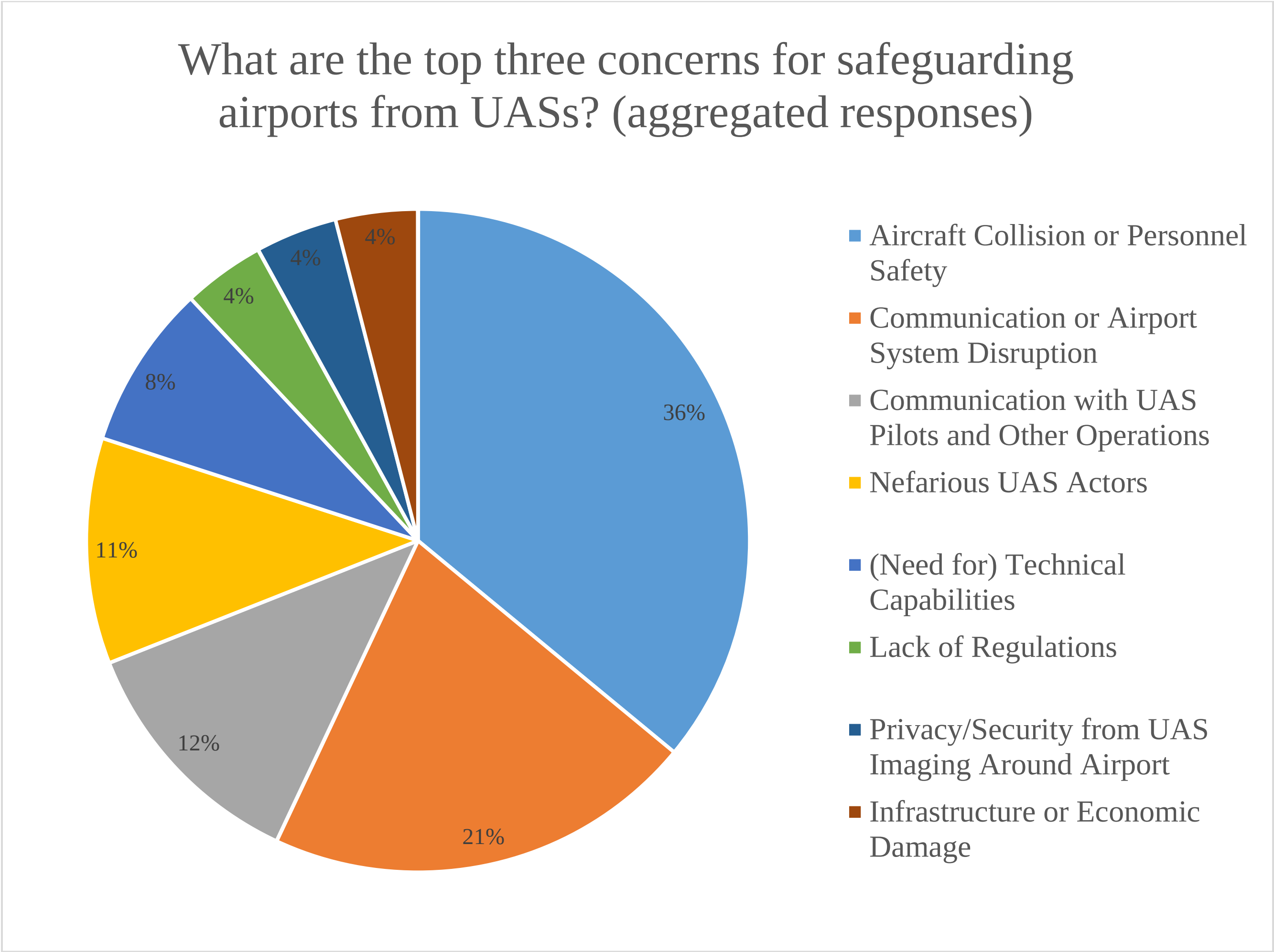
How supportive would you be of a motion to make geofencing mandatory for all commercial UASs and UAS operations?	A	B	C	D	AVERAGE
Score	1	7	5	2	3.75

Aggregated Responses
Respondent categories: Government, Law, Researchers, and Airport Operators (20 total)
(Number of Respondents per Question is Variable)

Table 28: Major reasons to safeguard airports

What are the top three concerns for safeguarding airports from UASs? (aggregated responses)	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	TOTAL	PERCENTAGE
Aircraft Collision or Personnel Safety	3	3	3	3	3	2		3		3		3				3	3		3		35	36%
Communication or Airport System Disruption												2	2	3	3	2	1	3	2	3	21	21%
Communication with UAS Pilots and Other Operations			2	2	2		2		2						2						11.5	12%
Nefarious UAS Actors				1			3	2	2							1	2				10.5	11%
(Need for) Technical Capabilities		2					1				3			2							8	8%
Lack of Regulations			1										3								4	4%
Privacy/Security from UAS Imaging Around Airport																		2		2	4	4%
Infrastructure or Economic Damage						1				2		1									4	4%

Figure 18: Major reasons to safeguard airport



6.5 Appendix E: COTS Counter-UAS Equipment Manufacturers

Table 29: Counter-UAS equipment manufacturers and products[**, ††]

Category	Company	Product
Hybrid	ELTA Systems Ltd, Israeli Aerospace Industries	Drone Guard
Hybrid	Airbus	Airbus Counter-UAV System
Hybrid	CACI	SkyTracker
Hybrid	Dedrone	DroneTracker Multi-Sensor
Hybrid	Department 13	MESMER
Hybrid	Selex ES (Leonardo, Finmeccanica)	Falcon-Shield
Hybrid	Liteye	Anti-UAV Defense System (AUDS)
Hybrid	Lockheed Martin	ICARUS
Hybrid	Rohde & Schwarz	ARDRONIS-I
Hybrid	SRC	Silent Archer
Detection	Adsys Controls Inc.	SATS2 Aerial Surveillance
Detection	Drone Go Home, LLC	RF Drone Detection
Detection	Robin Radar Systems BV	ELVIRA
Detection	C Speed LLC	LightWave Radar
Detection	DeTect	DroneWatcher
Detection	Domestic Drone Countermeasures	Basic Drone Detection System
Detection	Gryphon Sensors	Skylight
Detection	Gryphon Sensors	ACR Hawk
Detection	Sensofusion	AIRFENCE
Detection	SRC	AN/TPQ-5 with LSTAR/BSTAR Software
Interdiction	Delft Dynamics	DroneCatcher
Interdiction	OpenWorks	SkyWall
Interdiction	Theiss	EXCIPIO
Interdiction	Battelle	DroneDefender
Interdiction	Boeing	Boeing Laser System
Interdiction	HiGH + MiGHTY	SKYNET
Interdiction	M.A.L.O.U.	Drone Interceptor MPI 2

[**] Rows highlighted in red indicate that the company declined to participate in the survey; rows highlighted in gray indicate that the company provided product information; and rows with no highlight indicate the company did not respond to the Request for Information.
[††] Hybrid systems with both detection technologies and interdiction methods are incorporated in a single product.

Table 30: Performance attribute scales and weights

		Evaluation Scale (1–5)				
	Weight	**1**	**2**	**3**	**4**	**5**
Max Detection Range (km)	**10**	<1	≥1	≥3	≥5	≥8
Detection Probability	**10**	<0.85	≥0.85	≥0.9	≥.95	≥0.99
Max Intercept Range (km)	**10**	<1	≥1	≥2	≥3	≥5
Intercept Probability	**10**	<0.85	≥0.85	≥0.9	≥.95	≥0.99
Response Time (sec)	**10**	>180	≤180	≤120	≤60	≤30
Sensor Array	**10**	Sum of sensor values from description				
Azimuth Range (deg)	**8**	<45	≥45	≥90	≥180	≥360
Location Tracking Accuracy (m)	**8**	>300	≤300	≤100	≤25	≤5
Compatibility	**7**	No	N/A	N/A	N/A	Yes
Intercept Technology	**7**	Sum of sensor values from description				
UAS Speed Limits (km/hr)	**5**	<50	≥50	≥75	≥100	≥150
UAS Weight Limits (kg)	**5**	<3	≥3	≥5	≥10	≥25
Weight (kg)	**3**	>500	≤500	≤200	≤100	≤50

6.6 Appendix F: Technical Team

Table 31: Technical Team Members

Name	Org & Functional Area	Email	Phone
		MassDOT	
Jeff DeCarlo	Aeronautics Administrator	jeffrey.decarlo@state.ma.us	617-412-3686
Drew Mihaley	Inspector/Pilot/Investigator	Andrew.Mihaley@dot.state.ma.us	617-412-3692
Tom Mahoney	Chief Airport Engineer	Thomas.Mahoney@dot.state.ma.us	617-412-3678
Steve Rawding	Planning, Outreach & Education	Steven.Rawding@dot.state.ma.us	617-412-3691
Tracy Klay	Legal: Aeronautics Chief Counsel MassDOT/MBTA	tracy.klay@state.ma.us	617-973-7813
		Airport Operators: Massport	
Vince Cardillo	Senior Airport Ops	VCardillo@massport.com	Unk
		Airport Operators: MA Airports	
Katie Servis	Barnstable	katie.servis@town.barnstable.ma.us	508-775-2020
Ann Crook	Martha's Vineyard	ACrook@MVYAirport.com	508-693-7022
Mike Miller	Lawrence Muni Airport	M_Miller@lawrencemunicipalairport.com	978-794-5880
Bob Mallard	MAMA & Airport Engineer	rmallard@airportsolutionsgroup.com	Unk
		Federal Agencies	
Brendan Reilly	FAA ATC - Logan	brendan.reilly@faa.gov	Unk
Bryon Raykoff	FAA Airports	Bryon.Rakoff@faa.gov	781-238-7610
Michael O'Donnell	FAA Pathfinder – Dir Airport Safety & Stds (AAS-1)	Michael.J.ODonnell@faa.gov	202-267-8776
		Aircraft Operators	
Jeff DeCarlo	FW Prof Pilot-Airline /Military/GA	jeffrey.decarlo@state.ma.us	617-412-3686
Drew Mihaley	RW/FW Prof Pilot-Gov't/ Military/GA	Andrew.Mihaley@dot.state.ma.us	617-412-3692
Steve Rawding	FW GA	Steven.Rawding@dot.state.ma.us	617-412-3691
		MA State Police, and other Agencies & Associations	
John Hazelrigg	State Police Air Wing	john.hazelrigg@state.ma.us	978-686-9464
Steve Staffier	EOPPS (Comm Interoperability)	Steve.Staffier@MassMail.State.MA.US	617-274-5549
		Technical SMEs (Independent)	
David Pepyne	Systems Engineer, UMass	pepyne@ecs.umass.edu	Unk
Noel Zamot	Cyber Security	nzamot@corvusanalytics.net	781-452-2769
Michael Zinc	Electrical Engineer, UMass	mzink@cas.umass.edu	413-545-4465
Bob Mallard	Airport Engineer -Airport Solutions Group	rmallard@airportsolutionsgroup.com	Unk
TBD	Human Factors Scientist/Engineer (Aviation)		

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6.7 Appendix G: Counter-UAS Technology Evaluation Results

Appendix G provides the overall scoring used for evaluation of each of the counter-UAS systems. Values marked with an asterisk (*) were obtained from manufacturers' brochures and other publicly available sources.

Tables 32: Ground-based detection and tracking system performance scores

Adsys Controls Inc., SATS2 Aerial Surveillance				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**2**	**2**	**10**	**8.5**
Detection Probability	**0.9**	**3**	**10**	**12.8**
Sensor Array	**4**	**4**	**10**	**17.0**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**1.5**	**5**	**8**	**17.0**
Weight (kg)	**23**	**5**	**1**	**2.1**
TOTAL WEIGHTED SCORE				**74.5**

Drone Go Home, LLC, RF Drone Detection & Containment				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**3***	**3**	**10**	**12.8**
Detection Probability	**0.99**	**5**	**10**	**21.3**
Sensor Array	**2**	**2**	**10**	**8.5**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**50**	**3**	**8**	**10.2**
Weight (kg)	**13**	**5**	**1**	**2.1**
TOTAL WEIGHTED SCORE				**71.9**

* Values were obtained from manufacturers' brochures and other publicly available sources.

Robin Radar Systems, ELVIRA Drone Detection Radar				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**1.1**	**2**	**10**	**8.5**
Detection Probability	**0.9**	**3**	**10**	**12.8**
Sensor Array	**2.5**	**2.5**	**10**	**10.6**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**3.2**	**5**	**8**	**17.0**
Weight (kg)	**91**	**4**	**1**	**2.1**
TOTAL WEIGHTED SCORE				**67.7**

C Speed LLC, LightWave Radar				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**10***	**5**	**10**	**21.3**
Detection Probability	**0.8**	**1**	**10**	**4.3**
Sensor Array	**2.5**	**2.5**	**10**	**10.6**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**100***	**3**	**8**	**10.2**
Weight (kg)	**182**	**3**	**1**	**1.3**
TOTAL WEIGHTED SCORE				**64.7**

Gryphon Sensors, Skylight System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**10**	**5**	**10**	**21.3**
Detection Probability	**0.85**	**2**	**10**	**8.5**
Sensor Array	**5**	**5**	**10**	**21.3**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**50**	**3**	**8**	**10.2**
Weight (kg)	**91**	**4**	**1**	**1.7**
TOTAL WEIGHTED SCORE				**80.0**

* Values were obtained from manufacturers' brochures and other publicly available sources.

DeTect, DroneWatcher System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**3.2**	**3**	**10**	**12.8**
Detection Probability	**0.99**	**5**	**10**	**21.3**
Sensor Array	**5**	**5**	**10**	**21.3**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**50**	**3**	**8**	**10.2**
Weight (kg)	**182**	**3**	**1**	**1.3**
TOTAL WEIGHTED SCORE				**83.8**

Gryphon Sensors, Hawk System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**3.5**	**3**	**10**	**12.8**
Detection Probability	**0.9**	**3**	**10**	**12.8**
Sensor Array	**2.5**	**2.5**	**10**	**10.6**
Azimuth Range (deg)	**360**	**5**	**8**	**17.0**
Location Tracking Accuracy (m)	**12**	**4**	**8**	**13.6**
Weight (kg)	**34**	**5**	**1**	**2.1**
TOTAL WEIGHTED SCORE				**68.9**

Tables 33: Ground-based interdiction system performance scores

OpenWorks, SkyWall				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Intercept Range (km)	0.1	1	10	3.5
Intercept Probability	0.9	3	10	10.5
Response Time (sec)	181*	1	10	3.5
Compatibility	No	1	7	2.5
Intercept Technology	2	2	7	4.9
UAS Speed Limits (km/hr)	122	4	5	7.0
UAS Weight Limits (kg)	25	5	5	8.8
System Weight (kg)	12.8	5	3	5.3
TOTAL WEIGHTED SCORE				46.0

HiGH + MiGHTY Technologies, GmbH, SKYNET Anti Drone System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Intercept Range (km)	2*	3	10	10.5
Intercept Probability	0.99	5	10	17.5
Response Time (sec)	121*	2	10	7.0
Compatibility	No	1	7	2.5
Intercept Technology	4	4	7	9.8
UAS Speed Limits (km/hr)	150	5	5	8.8
UAS Weight Limits (kg)	25	5	5	8.8
System Weight (kg)	14	5	3	5.3
TOTAL WEIGHTED SCORE				70.2

* Values were obtained from manufacturers' brochures and other publicly available sources.

Battelle, DroneDefender				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Intercept Range (km)	0.25	1	10	3.5
Intercept Probability	0.99	5	10	17.5
Response Time (sec)	181*	1	10	3.5
Compatibility	No	1	7	2.5
Intercept Technology	4	4	7	9.8
UAS Speed Limits (km/hr)	150	5	5	8.8
UAS Weight Limits (kg)	25	5	5	8.8
System Weight (kg)	7	5	3	5.3
TOTAL WEIGHTED SCORE				59.6

Theiss UAV Solutions, LLC., EXCIPIO Aerial Netting System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Intercept Range (km)	2*	3	10	10.5
Intercept Probability	0.9	3	10	10.5
Response Time (sec)	121*	2	10	7.0
Compatibility	No	1	7	2.5
Intercept Technology	2	2	7	4.9
UAS Speed Limits (km/hr)	25	1	5	1.8
UAS Weight Limits (kg)	25	5	5	8.8
System Weight (kg)	5	5	3	5.3
TOTAL WEIGHTED SCORE				51.2

* Values were obtained from manufacturers' brochures and other publicly available sources.

Tables 34: Ground-based detection and interdiction hybrid system performance scores

Airbus DS Electronics and Border Security, Counter-UAV System				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	4.5	3	10	5.8
Detection Probability	0.8	1	10	1.9
Max Intercept Range (km)	1.5	2	10	3.9
Intercept Probability	0.99	5	10	9.7
Response Time (sec)	10*	5	10	9.7
Sensor Array	5	5	10	9.7
Azimuth Range (deg)	360	5	8	7.8
Location Accuracy (m)	100*	3	8	4.7
Compatibility	Yes	5	7	6.8
Interception Technology	4	4	7	5.4
UAS Speed Limits (km/hr)	150	5	5	4.9
UAS Weight Limits (kg)	25	5	5	4.9
System Weight (kg)	91	4	3	2.3
TOTAL WEIGHTED SCORE				**77.5**

Rohde & Schwarz, R&S ARDRONIS-I				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	1*	2	10	3.9
Detection Probability	0.9*	3	10	5.8
Max Intercept Range (km)	0.6*	1	10	1.9
Intercept Probability	0.99	5	10	9.7
Response Time (sec)	10	5	10	9.7
Sensor Array	2	2	10	3.9
Azimuth Range (deg)	360	5	8	7.8
Location Accuracy (m)	10*	4	8	6.2
Compatibility	Yes	5	7	6.8
Interception Technology	4	4	7	5.4
UAS Speed Limits (km/hr)	150	5	5	4.9
UAS Weight Limits (kg)	25	5	5	4.9
System Weight (kg)	73	4	3	2.3
TOTAL WEIGHTED SCORE				**73.2**

* Values were obtained from manufacturers' brochures and other publicly available sources.

Department 13, Inc., MESMER				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**1**	**2**	**10**	**3.9**
Detection Probability	**0.98***	**4**	**10**	**7.8**
Max Intercept Range (km)	**1**	**2**	**10**	**3.9**
Intercept Probability	**0.98**	**4**	**10**	**7.8**
Response Time (sec)	**60**	**4**	**10**	**7.8**
Sensor Array	**2**	**2**	**10**	**3.9**
Azimuth Range (deg)	**360**	**5**	**8**	**7.8**
Location Accuracy (m)	**100***	**3**	**8**	**4.7**
Compatibility	**Yes**	**5**	**7**	**6.8**
Interception Technology	**4**	**4**	**7**	**5.4**
UAS Speed Limits (km/hr)	**150**	**5**	**5**	**4.9**
UAS Weight Limits (kg)	**25**	**5**	**5**	**4.9**
System Weight (kg)	**41**	**5**	**3**	**2.9**
TOTAL WEIGHTED SCORE				**72.2**

Liteye System, Inc., Anti-UAV Defense System (AUDS)				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	**3**	**3**	**10**	**5.8**
Detection Probability	**0.9***	**3**	**10**	**5.8**
Max Intercept Range (km)	**1.5**	**2**	**10**	**3.9**
Intercept Probability	**0.99***	**5**	**10**	**9.7**
Response Time (sec)	**30**	**5**	**10**	**9.7**
Sensor Array	**4**	**4**	**10**	**7.8**
Azimuth Range (deg)	**360**	**5**	**8**	**7.8**
Location Accuracy (m)	**5**	**5**	**8**	**7.8**
Compatibility	**Yes**	**5**	**7**	**6.8**
Interception Technology	**4**	**4**	**7**	**5.4**
UAS Speed Limits (km/hr)	**150**	**5**	**5**	**4.9**
UAS Weight Limits (kg)	**25**	**5**	**5**	**4.9**
System Weight (kg)	**91**	**4**	**3**	**2.3**
TOTAL WEIGHTED SCORE				**82.5**

* Values were obtained from manufacturers' brochures and other publicly available sources.

Dedrone, DroneTracker				
Attribute	**Attribute Value**	**Attribute Score**	**Relative Weight**	**Parameter Weighted Score**
Max Detection Range (km)	3*	3	10	5.8
Detection Probability	0.8*	1	10	1.9
Max Intercept Range (km)	1*	2	10	3.9
Intercept Probability	0.9*	3	10	5.8
Response Time (sec)	30*	5	10	9.7
Sensor Array	5	5	10	9.7
Azimuth Range (deg)	360	5	8	7.8
Location Accuracy (m)	100*	3	8	4.7
Compatibility	Yes	5	7	6.8
Interception Technology	4	4	7	5.4
UAS Speed Limits (km/hr)	150	5	5	4.9
UAS Weight Limits (kg)	25	5	5	4.9
System Weight (kg)	205	2	3	1.2
TOTAL WEIGHTED SCORE				72.4

* Values were obtained from manufacturers' brochures and other publicly available sources.

Table 35: Detection and tracking systems evaluation results

	Weighted Performance Score	Minimum Durability Standards	Initial Cost ($ k)	Operational Cost ($ k)	Recommendation Notes
DeTect, DroneWatcher	83.8*	Meets Standards*	400	22	Strong
Gryphon Sensors, Skylight	80.0	Meets Standards	<1000	50	Strong
Adsys Controls, SATS2	74.5	Meets Standards	200	20	Strong
Drone Go Home	71.9	Meets Standards*	0	54	Acceptable
Gryphon Sensors, Hawk	68.9	Meets Standards	235	15	Acceptable
Robin Radar Systems, ELVIRA	67.7	Meets Standards	190	28	Acceptable
C Speed, LightWave Radar	64.7*	Meets Standards	<1000	20	Acceptable

Table 36: Interdiction systems evaluation results

	Weighted Performance Score	Minimum Durability Standards	Initial Cost ($ k)	Operational Cost ($ k)	Recommendation Notes
HiGH + MiGHTY, SKYNET	70.2*	No	35	unknown	Unacceptable*
Battelle, DroneDefender	59.6	Meets Standards	unknown	unknown	Acceptable*
Theiss, EXCIPIO	54.7	No	12	unknown	Unacceptable*
OpenWorks, SkyWall	46.0*	No*	unknown	unknown	Unacceptable

* Values were obtained from manufacturers' brochures and other publicly available sources.

Table 37: Detection and interdiction hybrid systems evaluation results

	Weighted Performance Score	Minimum Durability Standards	Initial Cost ($ k)	Operational Cost ($ k)	Recommendation Notes
Liteye, AUDS	82.5*	Unknown*	unknown	unknown	Strong
Airbus, Counter UAV System	77.5*	Meets Standards	unknown	unknown	Strong
R&S, ARDRONIS-1	72.6*	Meets Standards*	700	unknown	Strong
DeDrone, DroneTracker	72.4*	Meets Standards*	unknown	unknown	Acceptable
Department 13, MESMER	72.2*	Meets Standards	200	400	Acceptable

* Values were obtained from manufacturers' brochures and other publicly available sources.