US Patent & Trademark Office
Patent Public Search | Text View

ACOUSTIC BASED DETECTION AND AVOIDANCE FOR AIRCRAFT

Abstract

A method of analyzing of utilizing a detection and avoidance (DAA) model is disclosed. This includes analyzing by the DAA model a first audio signal to determine a first signal source associated with the first audio signal, generating, by the DAA model, a position and velocity estimation of the first signal source associated with the first audio signal. Then, classifying, by the DAA model, the first signal source as an air-based signal source based on the position and velocity estimation of the first signal source and generating, by the DAA model, a modification of a flight characteristic of the aircraft based on the classification of the first signal source and the position and velocity estimation of the first signal source.

Inventors: **Wyrobek; Keenan A. (Half Moon Bay, CA), Derry; Matthew O. (Ann Arbor, MI), Sant; Rohit H. (San Mateo, CA), Ananda Krishnan; Gavin K. (San Carlos, CA), Teisberg; Thomas O. (Menlo Park, CA), Demertzi; Michael J. (Half Moon Bay, CA)**

Applicant: **ZIPLINE INTERNATIONAL, INC.** (South San Francisco, CA)

Family ID: **1000008576664**

Appl. No.: **19/199063**

Filed: **May 05, 2025**

Related U.S. Application Data

Publication Classification

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. patent application Ser. No. 17/138,063, filed Dec. 30, 2020, which claims priority to and the benefit of U.S. Provisional Patent Application No. 63/082,838 filed Sep. 24, 2020 entitled "ACOUSTIC BASED DETECTION AND AVOIDANCE FOR AIRCRAFT", U.S. Provisional Patent Application No. 62/955,946 filed Dec. 31, 2019 entitled "UNMANNED AIRCRAFT SYSTEM WITH MICROPHONE ARRAY", U.S. Provisional Patent Application No. 62/984,266 filed Mar. 2, 2020 entitled "UNMANNED AIRCRAFT SYSTEM WITH MICROPHONE ARRAY", and U.S. Provisional Patent Application No. 63/021,633 filed May 7, 2020 entitled "UNMANNED AIRCRAFT SYSTEM WITH MICROPHONE ARRAY", the entire disclosures of which are incorporated herein in their entirety by reference.

BACKGROUND
[0002] Conventional aircraft detection systems, such as radar, may be difficult or cost prohibitive to incorporate into smaller aircraft, such as unmanned aircraft. Further, regulations may require unmanned aircraft to maintain a spherical detection zone, detecting other aircraft in every direction relative to the aircraft. As conventional aircraft detection systems may not be developed for such detection, implementing conventional systems for spherical detection may be technically complex and expensive.

[0003] Conventional aircraft, including commercial aircraft and general aviation aircraft, follow established airspace rules to avoid collision with other aircraft. For example, in general, each aircraft is responsible for the airspace in front of the aircraft. In some airspaces, unmanned aerial vehicles (UAVs) may be required to maintain spherical coverage, meaning that the UAV must monitor airspace in each direction for intruding aircraft. Further, UAVs may be responsible for moving out of the way of intruding aircraft, so that other aircraft do not encounter UAVs during flight. Conventional aircraft detection systems, such as radar, may be optimized for monitoring the area in front of an aircraft such that detection may be poor for obstructions or objects close to the ground, such as hills. While such systems may be altered to provide spherical coverage, a system providing such coverage may be prohibitively heavy relative to a UAV. Further, conventional detection systems may have difficulty with long-range detection, which gives a UAV less time to detect other aircraft and alter its flight path to avoid other aircraft.

SUMMARY
[0004] An audio signal received at audio sensors of an aircraft is analyzed to determine directional information for a source of the audio signal. A location of the source of the audio signal is determined based on the directional information.

[0005] One or more non-transitory computer readable media may be encoded with instructions which, when executed by one or more processors of an acoustic aircraft detection system, cause the aircraft detection system to analyze an audio signal received by the acoustic aircraft detection

system to determine directional information for a source of the audio signal and generate an estimation for a location of the source of the audio signal based on the directional information.

[0006] A multichannel audio signal is received at an acoustic detection system of an aircraft. A determination is made that the multichannel audio signal is associated with an intruding aircraft based on the multichannel audio signal. An initial maneuver is commanded for the aircraft.

[0007] An unmanned aerial vehicle (UAV) includes a plurality of acoustic sensors connected to the UAV and an acoustic detection system comprising one or more processors. The acoustic aircraft detection system analyzes audio signal received by the plurality of acoustic sensors to generate an estimation in a three dimensional space of an intruding aircraft relative to the UAV.

[0008] Additional embodiments and features are set forth in part in the description that follows, and will become apparent to those skilled in the art upon examination of the specification and may be learned by the practice of the disclosed subject matter. A further understanding of the nature and advantages of the present disclosure may be realized by reference to the remaining portions of the specification and the drawings, which form a part of this disclosure. One of skill in the art will understand that each of the various aspects and features of the disclosure may advantageously be used separately in some instances, or in combination with other aspects and features of the disclosure in other instances.

[0009] In another embodiment, a method is disclosed. The method may include receiving a first audio signal at audio sensors of an aircraft at a first position of the aircraft; analyzing, by a detection and avoidance (DAA) model at computing resources associated with the aircraft, the first audio signal to determine a first signal source associated with the first audio signal, wherein the DAA model is a machine learned model trained on acoustic data from known signal sources detectable during flight; generating, by the DAA model, a position and velocity estimation of the first signal source associated with the first audio signal; classifying, by the DAA model, the first signal source as an air-based signal source based on the position and velocity estimation of the first signal source; and generating, by the DAA model, a modification of a flight characteristic of the aircraft based on the classification of the first signal source and the position and velocity estimation of the first signal source.

[0010] In another embodiment, a system is disclosed. The system may include an aircraft; and a detection and avoidance (DAA) model at computing resources associated with the aircraft configured by instructions to perform operations including: receiving a first audio signal at audio sensors of an aircraft at a first position of the aircraft; analyzing the first audio signal to determine a first signal source associated with the first audio signal; generating a position and velocity estimation of the first signal source associated with the first audio signal; classifying the first signal source as an air-based signal source based on the position and velocity estimation of the first signal source; and generating a modification of a flight characteristic of an avoidance maneuver for the aircraft based on the classification of the first signal source and the position and velocity estimation of the first signal source.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The description will be more fully understood with reference to the following figures in which components are not drawn to scale, which are presented as various examples of the present disclosure and should not be construed as a complete recitation of the scope of the disclosure, characterized in that:

[0012] FIG. **1**A illustrates an example aircraft and an intruder.

[0013] FIG. **1**B illustrates an example aircraft and an intruder aircraft.

[0014] FIG. **2** is a schematic diagram of an example acoustic based detection and avoidance system

in accordance with particular embodiments.

[0015] FIG. **3** is a block diagram of an example acoustic based detection and avoidance system in accordance with particular embodiments.

[0016] FIG. **4** is a block diagram of an example model of an acoustic based detection and avoidance system.

[0017] FIG. **5** is a flow diagram of example steps for generating a state estimation of an intruder based on a captured audio signal.

[0018] FIG. **6** is a flow diagram of example steps for encounter determination using an acoustic based detection and avoidance system.

[0019] FIG. **7** is a flow diagram of example steps for commanding an initial avoidance maneuver based on a multichannel audio signal received by an acoustic based detection and avoidance system.

[0020] FIG. **8** is a flow diagram of example steps for training a model of an example acoustic based detection and avoidance system.

[0021] FIG. **9** is a schematic diagram of an example computer system implementing various embodiments in the examples described herein.

DETAILED DESCRIPTION

[0022] Audio based aircraft detection systems may provide an alternative to conventional detection systems for aircraft, especially those where conventional detection systems, such as radar, may be cost prohibitive or impractical to include, e.g., UAVs and other small aircraft. An audio based system may more readily provide spherical coverage without additional sensors facing in specific directions through the use of omnidirectional microphone, but in other instances, directional microphones may be used. For example, directional microphones may, in some implementations, be used in combination with omnidirectional microphones to gather additional information (e.g., to resolve front/back ambiguity). The audio based system can distinguish between noise produced by intruders, such as other aircraft, and noise produced by the aircraft's own engines (or flight system), distinguish between noise produced by intruders and natural sources (e.g., wind or weather noise), and determine directionality of sound (e.g., provide a location estimation of the intruder relative to the aircraft).

[0023] In one embodiment, the detection and avoidance (DAA) system uses an array of audio sensors to sense location of intruder in multiple directions relative to an aircraft, e.g., 360 degrees. Audio signals generated by intruders may be differentiated from, for example wind noise or noise from the aircraft, by comparing received audio signals to known other aircraft signals and rejecting signals assumed to not be associated with other aircraft, such as broadband signals (e.g., wind), non-directional signals, and near-field signals (e.g., noises from the aircraft's own engine). When an intruder signal is detected (i.e., presence of an intruder is detected) the DAA system determines location information for the intruder. For example, using the distance between the audio sensors on the subject aircraft and characteristics of the received intruder signal, the DAA system may calculate the azimuth of the intruder relative to the aircraft and estimate a relative location of the intruder. In some implementations, the system may analyze changes in the intruder signal as the aircraft moves relative to the intruder to determine the range and elevation of the intruder relative to the aircraft. It should be noted that although examples herein may discuss a single intruder, in some instances, there may be multiple intruders or sound sources. In these instances, the system may be configured to detect and estimate the location of two or more intruders and avoid each intruder as needed.

[0024] Using the estimated position of the intruder, the DAA system may utilize maneuvers or changes in a flight pattern for the aircraft to receive additional information about the intruder and/or avoid the intruder, where the avoidance may be based on avoiding a collision and/or maintaining a predetermined threshold or distance relative to the aircraft. For example, the DAA system may be selected to maintain a distance separation, e.g., 2,000 feet, between the subject

aircraft and intruders, such as intruding aircraft, and the flight pattern updates are selected to maintain such distance, as well as avoid a collision.

[0025] The DAA system may also be selected to maintain a clear zone (e.g., a spherical zone with a radius of 2,000 feet) around the subject aircraft. For example, rather than attempting to "avoid" an intruder, the DAA system may attempt to maintain a free or unobstructed volume, such as a sphere, or space. In these instances, the DAA system may generate flight path changes or maneuvers based on estimated intruder locations that are set to maintain the free airspace distance, rather than avoid a collision with the intruder and the UAV. To maintain a clear zone, the DAA system may detect an intruder and determine the general location of the intruder relative to the airspace and distancing. In the event of multiple intruders, intruders may be distinguished based on different locations relative to the subject aircraft, differences between audio signals generated by the intruders (e.g., different frequency bands), and other sound source separation techniques.

[0026] FIG. **1**A is a top perspective view of a relationship between an aircraft **100** using acoustic based DAA and an intruder **102**. FIG. **1**B is an example of the aircraft **100** and the intruder **102** as viewed from a side elevation. As shown in FIG. **1**A, the spatial relationship between the aircraft **100** and the intruder **102** may be defined in terms of azimuth θ, elevation angle Φ, and range R. With reference to the aircraft **100** and the intruder **102**, azimuth θ measures the angle between the aircraft **100** and the intruder **102** from the perspective of the aircraft **100**, where the angle θ is projected on a reference plane (shown in broken lines) parallel to the horizon. Elevation Φ is the angle between the aircraft **100** and the intruder **102** from the perspective of the aircraft **100**, where the angle Φ is projected on a reference plane perpendicular to the horizon. Range R is the radial distance between the aircraft **100** and the intruder **102**. The DAA system may allow the aircraft **100** to detect other aircraft within a spherical detection zone **101** (or other relevant detection area) such that the aircraft **100** can keep a spherical avoidance zone **103** clear of other intruders.

[0027] The DAA system may be used to determine whether an intruder is within the detection zone **101** of the aircraft **100** and to determine location information for the intruder, such as the azimuth θ, elevation angle Φ, and/or range R of an intruder **102**. Further, in some implementations, the DAA system may select maneuvers for the aircraft **100** to keep the avoidance zone **103** clear of intruders, including the intruder **102**.

[0028] The aircraft **100** may be provided with an audio array, including multiple audio sensors, such as omnidirectional microphones, mounted on the aircraft **100**. For example, the audio array may be implemented by the audio array described in U.S. Patent Application No. 63/082,869, Attorney Docket No. P288479.US.01, which is hereby incorporated herein in its entirety for all purposes. When a signal is received at the audio array, the DAA system **105** may determine whether the signal is likely associated with an aircraft by analyzing variations of a signal across sensors in the array. For example, where a signal is the same across all sensors and does not vary over time, the signal is likely either not directional and/or is associated with a close-range signal and is therefore not associated with an intruder. For example, noise from wind or motors of the aircraft **100** would be less likely to vary periodically and would likely result in a similar signal across various sensors. Where the signal is likely from an intruder, the DAA system may estimate the azimuth θ of the intruder **102** by analyzing variations in the audio signal across sensors and the distance between sensors.

[0029] To estimate the elevation angle Φ and range R of the intruder **102**, the DAA system may observe changes in the audio signal as the aircraft **100** moves relative to the intruder **102**. In some implementations, specific maneuvers may be used to gather additional data, e.g., force changes in the signal characteristics by changing positioning of the aircraft **100** to the intruder **102**. For example, the aircraft **100** may rotate along its roll axis while the DAA system analyzes the audio signal to generate an estimation of the elevation angle Φ and range R of the intruder **102**.

[0030] The azimuth θ, elevation angle Φ, and/or range R provide a state estimation of the intruder **102**, which may be used by systems of the aircraft **100** to maneuver away from the intruder **102** or

to otherwise update a flight path to maintain a desired separation between the aircraft **100** and the intruder **102**. In some implementations, the DAA system may continually generate state estimations for the intruder **102** to track the intruder **102**. Further, the DAA system may incorporate data from additional sensing modalities (e.g., image data, radar, light detection and ranging (LiDAR), or automatic dependent surveillance-broadcast (ADS-B) sensors).

[0031] FIG. **2** shows example hardware diagram used to implement a DAA system. A DAA node **106** includes processing **108** and memory **110** that may analyze audio signals received at microphones **114***a-n.* Array elements **112***a-n* may format or process signals received by microphones **114***a-n* before the signals are provided to the DAA node **106** for processing and analysis. The DAA node **106** may also communicate with aircraft control **104** such that the DAA node **106** can command the aircraft **100** to perform a variety of maneuvers.

[0032] Microphones **114***a-n* may be mounted on the aircraft **100** at locations selected to minimize noise perceived by the microphones **114***a-n.* For example, in some implementations, the microphones **114***a-n* may be mounted on probes connected or attached to wings of the aircraft **100**. Additional microphones may be mounted elsewhere on the aircraft **100**. In various implementations, the microphones **114***a-n* may be omnidirectional microphones or may be implemented by a combination of omnidirectional microphones, directional, and/or other microphones. The microphones **114***a-n* may be implemented to provide a digital signal or an analog signal. Collectively, the audio signals collected at the microphones **114***a-n* provide a multichannel audio signal to the DAA system.

[0033] Array elements **112***a-n* may be implemented by various hardware capable of capturing and processing signals from the microphones **114***a-n.* For example, in one implementation, the array elements **112***a-n* may be implemented using programmable logic to digitize analog audio signals collected at the microphones **114***a-n.* In other implementations, array elements **112***a-n* may be implemented using other types of hardware including microcontrollers, system on chip (SOC) hardware, and other types of compute resources.

[0034] DAA node **106** includes processing **108** and memory **110**. Memory **110** may be implemented using any combination of volatile and non-volatile memory. Processing **108** may include one or more processors operating individually or in combination and may include, for example, programmable logic and other processors. In various implementations, the DAA node **106** may be implemented by SOC hardware, a microcontroller, or various compute resources. The DAA node **106** may also be implemented by combinations of various types of compute resources. For example, in one implementation, the DAA node **106** includes a controller board and a microcontroller.

[0035] Aircraft control **104** may include various systems to control the aircraft **100** and to communicate with ground station and other aircraft. For example, aircraft control **104** may include transmitting and receiving hardware for communications via very high frequency (VHF) radio bands, satellite communications, cellular communications, or communications via additional radiofrequency bands. Aircraft control **104** may include various components and modules responsible for generating a flight plan for the aircraft **100**, actuator control, propulsion control, payload management, and safety system management, among others. The aircraft control **104** may be implemented by any number of hardware components including SOC hardware, various processors, controllers, and programmable logic.

[0036] Various hardware components of the DAA system may be communicatively connected by communications buses, universal serial bus (USB) connections, or other communicative connections.

[0037] FIG. **3** shows a block diagram of an example DAA system. The blocks of the example DAA system may be implemented using a variety of algorithms, models, programming, or combinations of any number of algorithms, models, and other programming. In some implementations, instructions corresponding to the blocks of the DAA system may be executed using the same

processor (e.g., DAA node **106**). In other implementations, some instructions may be executed by processors on different boards or by different processors on a shared board. For example, instructions for signal capture **120** and signal processing **122** may be executed by processors at array elements **112***a***-112***n,* while localization **124**, encounter determination **126**, and tracking **128** may be executed using processing resources **108** at the DAA node **106**. Further, instructions for one block of the DAA system may be executed at multiple locations. For example, initial signal processing **122** instructions may be executed at array elements **112***a***-112***n,* while further signal processing **122** may occur at the DAA node **106**.

[0038] One or more blocks of the example DAA system may be implemented using machine learning models, including deep learning networks. In some implementations, several blocks of the DAA system may be implemented by a single model or using combinations of models that work cooperatively. For example, in one implementation localization **124** and encounter determination **126** may be implemented by a shared deep neural network.

[0039] Instructions for signal capture **120** may include algorithms to timestamp received audio signals and align audio signals across channels to generate a multichannel audio signal. In some implementations, signal capture **120** may include converting analog signals to digital signals for processing. Signal capture **120** may occur at array elements **112***a-n,* the DAA node **106**, or a combination of the array elements **112***a-n* and the DAA node **106**. For example, in some implementations, incoming analog signals may be converted to digital signals and time stamped at respective array elements **112***a-n* and the digital signals may be aligned to form a multichannel audio signal at the DAA node **106**.

[0040] Instructions for signal processing **122** may include algorithms and machine learning models for transforming a multichannel audio signal. Which algorithms or models are included in signal processing **122** may be dependent upon methods implemented by the DAA system to analyze the multichannel audio signal. For example, in one implementation, the DAA system includes a model for localization that receives three-dimensional frequency domain data as input and signal processing **122** includes a fast Fourier transform (FFT) algorithm to transform the multichannel audio signal to the frequency domain. In another implementation, signal processing **122** may occur within a deep neural network implemented by the DAA system. In some implementations, signal processing **122** may include filtering out extraneous noise from the multichannel audio signal. For example, signal processing **122** may identify broadband wind signals and filter those signals from the multichannel audio signal.

[0041] Instructions for localization **124** may be implemented using various combinations of algorithms and machine learning models depending on the localization method implemented by the DAA system. For example, localization **124** may include algorithms for beamforming of a multichannel audio signal and additional algorithms for analyzing the beamformed audio signal to determine directionality. In another example implementation, localization **124** may be implemented using multiple binary classifiers representing bins of azimuth angles to generate an estimation of azimuth. In yet another example implementation, localization **124** may be implemented using a deep neural network generated using labeled multichannel audio and directional data. Localization **124** may also include machine learning models, algorithms, or combinations to determine range and elevation based on audio signals gathered during motion of the aircraft **100**. Further, in some implementations, localization **124** may be implemented using models that combine multichannel audio signals with signals from additional sensing modalities (e.g., LiDAR, radar, and ADS-B) to generate estimations of location of an intruder aircraft **102**.

[0042] Aircraft maneuvering **130** may be implemented to provide instructions for specific aircraft maneuvers or changes to the flight plan for the aircraft **100** to the aircraft control **104**. Accordingly, aircraft maneuvering may include instructions to various components of the aircraft control **104** (e.g., instructions for actuation control and propulsion control) to initiate various aircraft maneuvers. In some implementations, the instructions provided to the aircraft control **104** by

aircraft maneuvering **130** may be dependent on estimations generated by localization **124**.

[0043] Encounter determination **126** may be a module making an initial determination of whether a received audio signal is associated with one or more likely intruders. For example, an encounter may be determined when a sound source indicates the presence of one or more intruders within a spatial area surrounding the UAV, within a distance relative to the UAV, or other threshold selected by the system. In the method, the encounter determination **126** may be implemented by various combinations of algorithms and/or machine learning models to generate a likelihood that a received multichannel audio signal is associated with an intruder **102**. In some implementations, encounter determination **126** may be implemented using a deep neural network generated using multichannel audio signals from known aircraft. In some implementations, the deep neural network may be the same deep neural network used for localization **124**. In another example implementation, encounter determination **126** is implemented using a classifier, which may be, for example, a random forest classifier or a binary classifier. In yet another implementation, encounter determination **126** may be implemented using algorithms and models to compare a received multichannel audio signal to known audio signals associated with aircraft. For example, the blade pass frequencies of aircraft may be utilized to generate multiple filters showing frequencies associated with aircraft. The multichannel audio signal (or a representation of the multichannel audio signal generated by signal processing **122**) may be cross correlated or otherwise compared to the filters to determine whether the signal is associated with an aircraft. In some implementations, encounter determination **126** may also include models and algorithms to identify a specific type of aircraft during the cross-correlation process.

[0044] Tracking **128** or location identification may be implemented by data structures, algorithms, or a combination thereof to track or otherwise determine a location of an intruder **102**, or multiple intruders, over time based on state estimations from localization **124**. In some implementations, tracking **128** may be implemented including algorithms, models, or various combinations of algorithms and models to determine whether a received state estimation belongs to an already existing track or whether a new track should be created for a state estimation. For example, a data point may be associated to a track or location using a Hungarian algorithm and the maintenance and updating of a track or a location may include application of one or more Bayesian filters and Monte-Carlo methods. In some examples, a prior track history may be updating based on new information using iterative smoothing and mapping (iSAM2). In other examples, a "track" or location update may be determined and updated using different filters and algorithms as desired, as well as may include a combination of one or more methods, such as utilizing probabilistic tracking (e.g., Bayseian filtering, Kalman filtering, Monte-Carlo methods) to determine a source location after some aspects have been determined by ML or deep learning models. The various blocks of the DAA system may be, in some implementations, implemented by common models. Generally, the various blocks are communicatively connected and cooperatively process and analyze multichannel audio data.

[0045] FIG. **4** shows an example DAA model **132**, including inputs received by the DAA model **132** and outputs generated by the DAA model **132**. The DAA model **132** may be implemented as machine readable instructions located at memory **110** of the DAA node **106** and executed by processing **108** of the DAA node **106**. The DAA model **132** may be used to implement various blocks of the example DAA system described in FIG. **3**. For example, in one implementation, the DAA model **132** is used to implement both localization **124** and encounter determination **126**. In other implementations, the DAA model **132** may also include signal processing **122**, aircraft maneuvering **130**, and some portions of tracking **128**. The DAA model **132** may receive initial multichannel audio data **134** and generate an aircraft probability **136** and an intruder azimuth **138** based on the initial multichannel audio data **134**. The DAA model **132** may also receive maneuver multichannel audio data **140** and generate an intruder range and elevation **142** based on the maneuver multichannel audio data **140**.

[0046] The DAA model **132** may be implemented using a variety of machine learning models, including combinations of several machine learning models, and/or a combination of machine learning models and probabilistic filtering. For example, in one implementation, the DAA model **132** may be implemented using a deep learning model, such as a deep neural network or recurrent neural network. In other implementations, the DAA model **132** may include one or more of or a combination of a random forest model regressor or binary classifier, or multiple binary classifiers, or similar classifiers. Other types of machine learning models or combinations of machine learning models may be used to implement the DAA model **132** and the type of model used to implement the DAA model may be partially dependent on the type of data used as input to the DAA model **132**. For example, where the initial multichannel audio data **134** is provided in the time domain, the DAA model **132** may be implemented by a recurrent neural network. In other implementations, the initial multichannel audio data **134** may be formatted as image data in the frequency domain and the DAA model **132** may be implemented by a convolutional neural network. For example, image data may have multiple channels representing multiple frequency transformations such that frequencies with harmonic relationships relative to each other are collocated in the same pixel region on different channels. This type of image data facilitates a convolutional filter to discover harmonic relationships when considering a limited subset of pixels. In some implementations, a deep neural network (e.g., a recurrent neural network or convolutional neural network or transformer) may be combined with various types of classifiers or other machine learning models to implement the DAA model **132**.

[0047] The initial multichannel audio data **134** may, in some implementations, be provided as input to the DAA model **132** with little or no processing after being collected by the audio array. For example, the initial multichannel audio data **134** may be provided to the DAA model **132** one-dimensional time domain data for each of the channels in the initial multichannel audio signal. In other implementations, the initial multichannel audio data **134** may be transformed to the frequency domain before being provided to the DAA model **132**. Two-dimensional frequency domain data may include frequency and phase data for each of the channels included in the multichannel audio data **134**. Three-dimensional frequency domain data may include time, frequency, and phase data for the multichannel audio signal. Other pre-processed data may be provided as the initial multichannel audio data **134**, such as a beamformed spectrogram including time, frequency, and signal intensity or a feature vector generated using a harmonic kernel bank. In some implementations, other data sources, such has motor telemetry data from other sensors on the aircraft, may be pre-processed and layered with the multichannel audio data to help the models determine which sounds are generated by the aircraft and which sounds originate elsewhere.

[0048] The aircraft probability **136** may be provided as a probability that the signal captured in the initial multichannel audio data **134** is associated with an intruder. In some implementations, the aircraft probability **136** may include a decision (yes or no) with a confidence interval or probability relating to the decision. In other implementations, the aircraft probability **136** may include probabilities that the audio signal is associated with different classes or types of aircraft. For example, the aircraft probability **136** may include a probability that the signal is associated with a general aviation aircraft, a helicopter, or the like. As another example, the audio signal may be characterized as being associated with a more specific range of aircraft, e.g., heavy jet, light jet, narrow body aircraft, or the like. The classification may assist the system in making decisions regarding maneuvers to either avoid the intruder and/or maintain a free airspace, since information, such as the expected flight elevation, velocity ranges, and the like, may be extracted and utilized by the system based on the classification of the type of aircraft. In some instances, the probability may include an assessment that the probability is associated with an aircraft (or may be framed in the opposite manner, that the signal is not an aircraft).

[0049] The intruder azimuth **138** may be presented as an angle with a confidence interval or may include probabilities for multiple ranges of angles. For example, in one implementation each angle

relative to the aircraft **100** may be included in a bin of angles. Various numbers of bins may be used. In one example, **64** bins are included in the analysis, where each bin includes a range of angles of 5.625°. For example, a bin included in the analysis includes angles from 0-5.625° and another bin includes angles from 354.375-360°. The returned intruder azimuth **138** may include a probability that the intruder azimuth is within each of the candidate bins. The returned intruder azimuth may also include probabilities for a certain number of bins. For example, probabilities may be returned for the five bins with the highest probability of including the intruder azimuth **138**. In some implementations, the intruder azimuth **138** may be calculated only if the aircraft probability **136** indicates a strong likelihood that the multichannel audio signal is associated with an intruder **102**.

[0050] Where the aircraft probability **136** returns showing a likelihood that the initial multichannel audio data **134** is associated with an intruder **102** and the intruder azimuth **138** is determined, the DAA system may instruct various maneuvers to collect maneuver multichannel audio data **140**. The maneuver multichannel audio data **140** is generally multichannel audio data collected during a known maneuver of the aircraft **100**, during controlled movement of sensors (e.g., microphones **114***a-n*), or combinations of various types of known movement. Accordingly, the maneuver multichannel audio data **140** may be represented in the various forms described with respect to the initial multichannel audio data **134** and may also include information (e.g., time of maneuver, amplitude, angle, etc.) regarding the maneuver of the aircraft **100**.

[0051] The intruder range and elevation **142** may be generated by the DAA model **132** based on the maneuver multichannel audio data **140** and may be presented in similar representations as those discussed with respect to the intruder azimuth **138**. For example, the intruder elevation may be represented by several bins of angles with probabilities that the intruder elevation is included in each bin. The intruder elevation may also be represented by an estimated angle and a confidence interval corresponding to the estimated angle. Similarly, the intruder range may be represented as an estimated range accompanied with a confidence interval.

[0052] A combination of the intruder azimuth **138** and intruder range and elevation **142** may be used to generate a state estimation or location estimation for the intruder aircraft **102** in three-dimensional space. In some implementations, as data is continually collected and processed by the DAA system, multiple state estimations may be aggregated to track and intruder aircraft **102** with respect to the aircraft **100**. Such tracks may be used, in some implementations, to select avoidance maneuvers for the aircraft **100**.

[0053] In various implementations, the state estimation or location estimation may estimate the location using an audio signal (e.g., from the DAA system) and a second signal. The second signal may be another audio signal collected at a different point in time or a signal collected using a different sensor modality, such as ADS-B In, LiDAR, radar, image data or vision-based signal, GPS, or other sensor modalities. For example, in one implementation, an audio signal may be used in conjunction with a vision-based signal (e.g., a camera) to generate a location estimation. In this example, the audio signal may provide a rough approximation of location (e.g., there is likely an intruder on the left side of the aircraft), while a vision-based signal may refine an estimation generated from the audio signal. In other words, the first signal may be used to determine general location information that may be detected from a farther distance and the second signal may be used to determine more accurate or sensitive location information, that may be detected from a closer distance to the source. In these instances, the first signal may be used to determine when to actuate sensors for the second signal, e.g., once the first signal has been used to detect an intruder within a particular distance threshold of the aircraft, the system can then actuate the second sensor and detect the second sensor signal. Further, in some implementations, three or more different signals (differing in collection time, sensing modality, or both collection time and sensing modality) may be used to generate a location estimation.

[0054] FIG. **5** is a flow diagram of example steps for generating a state estimation of an intruder

based on a captured or otherwise detected audio signal. A capturing operation **202** captures an audio signal. For example, one or more of the microphones **114***a-n* may detect audio signals during the capturing operation **202**. The capturing operation **202** may detect audio signals around the aircraft **100**, including, in some examples, audio signals not associated with intruders. Further, in some implementations, other sensing modalities may capture signals during the capturing operation **202**. For example, ADS-B receivers or LiDAR detectors may capture signals as the microphones **114***a-n* capture audio signals.

[0055] A processing operation **206** processes the signal to format the signal for further analysis, if needed. The processing operation may be implemented by the signal processing block **122** of the DAA system. In some implementations, some portions of the processing operation **206** may be performed at the localization block **124** of the DAA system. Accordingly, portions of the processing operation **206** may be performed by the DAA model **132**.

[0056] The processing operation **206** may, in various implementations, include transforming an analog signal to a digital signal, time aligning the multichannel audio signal, domain transforming the signal, beamforming the signal, or otherwise adjusting the signal to optimize the signal to noise ratio (SNR) of the signal. For example, in one implementation, the processing operation **206** time stamps the multichannel audio signal. In another implementation, the processing operation **206** transforms the multichannel audio signal to the frequency domain, resulting in either a two dimensional frequency domain signal for each channel of the multichannel audio signal or a three dimensional frequency domain signal representing the multichannel audio signal. The processing operation **206** may use, for example, an FFT algorithm to transform the signal. The processing operation **206** may also implement a beamforming algorithm to generate a beamformed spectrogram representing the multichannel audio signal. The processing operation **206** may, accordingly, generate initial data **134** provided to the DAA model **132**, in some implementations.

[0057] The processing operation **206** may determine whether the captured signal is directional and/or distanced from the aircraft (e.g., not a near-field signal). The directionality determination may be done implicitly (e.g., via beamforming) or explicitly. In some examples, the DAA system **105** may attempt to time align the multichannel audio signal. For example, where a signal is not periodic (e.g., does not vary in a pattern over time), the signal will likely not time align across multiple channels. Where the multichannel audio signal is capable of being time aligned, the signal is likely coherent and directional. In instances where the multichannel audio signal is not capable of being time aligned across channels, the signal can be assumed to be incoherent and not directional. An incoherent or non-directional signal is typically one that is not produced by one localized sound source (e.g., another aircraft) and may instead be attributed to other sources, such as wind or weather.

[0058] In some implementations, a determination of whether the captured signal is directional may be made implicitly during the operation **208**. For example, all incoming signals may be processed during operation **206** and a determination of directionality may be part of the determination of whether the processed signal has a structure typical of aircraft. For example, directionality may be determined as part of the determination of whether the processed signal has a structure typical of an aircraft. For example, a beamformed signal that is non-directional may not correlate to harmonic kernel filters mimicking the signals expected from aircraft. Similarly, a near-range audio signal many not correlate to harmonic kernel filters designed to mimic farther range audio signals.

[0059] In some implementations, an explicit determination of directionality may be made by, for example, looking for specific characteristics of a processed audio signal specifically to determine directionality. For example, the DAA system may reject broadband signals as non-directional. The system may also look for other characteristics of directional signals, such as periodicity, to determine directionality explicitly.

[0060] In the operation **208**, the processed signal is analyzed to determine whether the processed signal has a structure typical of an aircraft. The operation **208** may be part of the encounter

determination **126** of the DAA system. In some implementations, the DAA model **132** may analyze the processed signal based on the initial multichannel audio data **134**. During the operation **208**, the DAA model **132** may compare the initial multichannel audio data **134** to multichannel audio data known to correspond to aircraft. In other implementations, the operation **208** may include cross-correlating the processed multichannel audio data to a bank of filters, which may be harmonic kernel filters. Harmonic kernel filters may represent the signal expected from an aircraft based on the blade pass frequency of the aircraft. Generally, harmonic kernels may be generated for a range of aircraft expected to be encountered. For example, harmonic kernels may be generated for specific aircraft (e.g., a specific make and model) and/or may be generated for a class of aircraft (e.g., aircraft that use propellers, heavy jets, or the like). In instances where the filters may be generic across a range or class of aircraft, the filters can be more broadly applicable to possible audio sources as compared to more specific filters. That said, with more specific filters that more closely match with the exact type of aircraft, the assumptions and inputs may be more relevant to the audio signal source.

[0061] The harmonic kernel filters may include a base frequency and multiple harmonic frequencies corresponding to the base frequency. Where the multichannel audio signal does not correlate to the bank of harmonic kernel filters, the operation **208** may determine that the multichannel audio signal does not have a structure typical of an aircraft. Where the multichannel audio signal does strongly correlate with a harmonic kernel filter, the operation **208** may determine that the processed signal does have a structure typical of an aircraft. Correlation with a filter may be determined, for example, by image comparison, where an image representing the signal is compared to the filters, represented as images, to determine whether the signal resembles an expected idealized harmonic signal.

[0062] Where the processed signal does not have a structure typical of an aircraft, the method returns to the capturing operation **202**. Where the processed signal does have a structure typical of an aircraft, an optional step **210** may receive additional data from other sources. For example, ADS-B In data from the aircraft **100**, ground-based LiDAR data, or other data from ground or aircraft based sensors may be received during the optional step **210**. Such data may be used, for example, by the DAA model **132** to generate a state estimation of the intruder **102**. The state estimation may be used by the aircraft **100** to track the intruder over time or to determine a course of action for keeping the avoidance zone **103** clear of the intruder **102**.

[0063] A commanding operation **212** commands a gathering maneuver, such as one that may be selected to gather more information and/or increase a distance or separation between the sound source and the aircraft **100**. Where the operation **208** determines that the multichannel audio signal has a structure typical of an aircraft, the commanding operation **212** may command a maneuver to determine changes in the multichannel audio signal behavior as the aircraft **100** moves relative to the intruder **102**. The criteria for determining whether the multichannel audio signal has a structure typical of an aircraft may be lower or otherwise different than criteria used for determination. For example, a maneuver may be initiated based on a suspicion that the multichannel audio signal belongs to an aircraft. Such maneuvers allow the DAA system to determine additional location information for the intruder, which may help to determine or refine estimations for azimuth, elevation, and range for the intruder **102**, as well as increase a separation between the intruder **102** the aircraft **100**. The commanding operation may be implemented at aircraft maneuvering **130**, by communicating an information gathering maneuver from the DAA node **106** to aircraft control **104**. As mentioned, in some implementations, the maneuver may be an avoidance maneuver, which moves the aircraft **100** to a location where a collision with another aircraft (including the intruder **102**) is statistically less likely. For example, an avoidance maneuver may reduce the altitude of the aircraft **100** as encounters with other aircraft may be less likely at lower altitudes. In other implementations, the information gathering maneuver may be configured to generate information by moving in a specific axis. For example, a "wing wag" maneuver may move the wings of the

aircraft **100** (and, accordingly the audio sensors) along a roll axis of the aircraft **100** to capture changes in the multichannel audio signal behavior during the wing wag maneuver. Other maneuvers, such as a roll or crab maneuver, may also be used as information gathering maneuvers. The information gathering maneuver may, in some implementations, include multiple individual maneuvers and may include very small or micro maneuvers.

[0064] A generating operation **214** generates a state estimation of the intruder. The state estimation of the intruder may include intruder characteristics, such as, but not limited to, the azimuth, elevation, velocity, range, and/or fundamental frequency of the intruder **102** relative to the aircraft **100**. In some implementations, the state estimation may include only one or two of the above coordinates. The generating operation **214** may be based on data collected as a multichannel audio signal and may, in some implementations, incorporate additional data from other sensor modalities. Further, the generating operation **214** may occur in sub-operations. For example, in some implementations, the azimuth of the intruder **102** may be determined before the commanding operation **212** and the elevation and range of the intruder **102** may be determined after the commanding operation **212** by analyzing changes in the multichannel audio signal as the aircraft **100** executes an information gathering maneuver. The generating operation **214** may occur at localization **124** of the DAA system.

[0065] In some implementations, the generating operation **214** is carried out by the DAA model **132**. In some implementations, the DAA model **132** may generate the state estimation based on maneuver multichannel audio data **140**. In other implementations, the DAA model **132** may use initial multichannel audio data **134** to generate the intruder azimuth **138** and use maneuver multichannel audio data **140** generated in response to the commanding operation **212** to generate the intruder range and elevation **142**. The DAA model **132** may determine the intruder azimuth **138** using, for example, a mean standard deviation to estimate the azimuth and a confidence interval for the estimation. The DAA model **132** may also generate an estimation of the azimuth based on known data used to train or generate the DAA model **132**. In some implementations, this may include using multiple classifiers each representing a bin of angles to determine the probability that the azimuth of the intruder **102** is within a respective bin. In other implementations, the DAA model **132** may use additional or alternate approaches to calculate the intruder azimuth **138**.

[0066] In some implementations, the azimuth may be determined using algorithms not included in the DAA model **132**. For example, where the processing operation **206** generates a beamformed spectrogram representing the multichannel audio signal, the intruder azimuth may be determined by identifying the phase shift or angle bin (e.g., an angle bin on the beamforming source map) corresponding to the highest intensity signal. For example, the location on the spectrogram where the signal is highest in intensity (e.g., highest dB) correlates to a phase angle, which may be used to approximate the azimuth. Other algorithms may also use the multichannel audio signal and the geometry of the array (e.g., known distances between microphones **114***a-n*) to determine or estimate the intruder azimuth.

[0067] The intruder range and elevation **142** may be determined by the DAA model **132** using maneuver and multichannel audio data **140** generated responsive to the commanding operation **212**. In some implementations, the DAA model **132** may compare the behavior of the signal during the information gathering maneuver to known data to estimate the intruder range and elevation **142** or by observing changes of magnitude of the signal during the information gathering maneuver. In other implementations, the DAA model **132** may use other methods to determine the intruder range and elevation **142** based on the maneuver multichannel audio data **140**. For example, in some implementations, the geometry of the microphones may be changed by actuating the microphones during flight, which may generate data used by the DAA model **132**. Actuation of the microphones by a known amount (e.g., a known displacement) or known variation, while measuring how the audio signal changes as a result of the displacement may provide additional data about the audio signal source including location, velocity, and the like. Further, in some implementations, the

intruder range and elevation may be generated without use of the DAA model **132**, using algorithms incorporating the changes in position of the various array elements as a result of the information gathering maneuver and the behavior of the multichannel audio signal at various channels responsive to the information gathering maneuver.

[0068] In some implementations, additional operations may use the state estimation generated by the generating operation **214** to track an intruder as it moves relative to the aircraft **100**. Such tracking may be used to determine whether an initial avoidance maneuver was sufficient to avoid an intruder, whether the maneuver has kept the avoidance zone **103** of the aircraft **100** clear, what types of avoidance maneuvers are best for avoiding an intruder and/or keeping the avoidance zone **103** clear of intruders, and to refine estimations of the location of an intruder. In some implementations, the state estimation and tracks generated based on multiple state estimations may be transmitted to, for example, a ground control station for the aircraft **100**.

[0069] FIG. **6** is a flow diagram of example steps for encounter determination using an detection and avoidance system. In some implementations, the operations described with respect to FIG. **6** may occur as part of the processing operation **206** and the operation **208** described above with respect to FIG. **5**. In some implementations, some or all of the operations of FIG. **6** may be carried out using the DAA model **132**. A transforming operation **302** transforms time aligned captured audio signals to the frequency domain. The transforming operation **302** may use, for example, a FFT algorithm to transfer time domain signals to frequency domain signals. In various implementations, the transforming operation **302** may produce two-dimensional frequency domain signals or three-dimensional frequency domain signals. A beamforming operation **304** beamforms the transformed signal. Various beamforming algorithms, such as minimum variance beamforming, may be used to generate a beamformed spectrogram from the transformed signal. The beamformed spectrogram generally shows a signal obtained by combining the signals received at the various channels of the array. The beamformed signal may, for example, use constructive interference between the various signals to strengthen the signal of interest (e.g., signals in frequencies associated with intruders). A generated spectrogram **314** may map frequency over time, where color variations indicate signal strength. For example, in the spectrogram **314**, shown in greyscale, white color may correlate to a high strength or high intensity signal, while a black color correlates to no signal, and the shades of grey between the two indicate variations in strength. Other color schemes or computer readable elements may also be used in various implementations to indicate variations in strength or intensity of a signal.

[0070] A pre-processing operation **306** pre-processes the beamformed signal. For example, the pre-processing operation **306** may convert the spectrogram **314** to the processed signal **316**. The pre-processing operation **306** may, for example, disregard signals at below a threshold intensity to simplify the spectrogram **314**. For example, the processed signal **316** includes less minor variations by eliminating low intensity signals from the spectrogram **314**, while retaining frequency signals of interest. In some implementations, the method may proceed directly from the pre-processing operation **306** to a generating operation **312**. For example, where a deep learning model implements the DAA model **132**, the optional operations **308** and **310** may not be needed to generate the estimation of the generating operation **312**. Specifically, the deep learning model, such as a deep neural network, may be generated such that the model can receive processed signals as input and determine whether the signal is associated with an intruder and an approximation of the location of the source of the audio signal, without the need to generate estimation and generator operations. In other words, the model can use the input data, along with its trained data set to automatically determine the association of the signal with an intruder. Accordingly, the model may not use harmonic filters and feature vectors as described with respect to operations **308** and **310**.

[0071] An optional identifying operation **308** identifies a highest correlated filter to the signal to identify the intruder. As one example, the identifying operation **308** may compare the processed signal **318** to a bank of harmonic kernel filters (e.g., harmonic kernel filter **320**) to locate the filter

most highly correlated with the processed signal **318**. The harmonic kernel filters may include a filter for each blade pass frequency likely to be encountered during flight. For example, the bank of harmonic kernel filters may include harmonic kernel filters using base frequencies between 12 Hz and 136 Hz, with a harmonic kernel filter at each increment of 2 Hz. The harmonic kernel filters mimic expected harmonic structure, where a high intensity signal is expected at the base frequency along with additional signals at each harmonic associated with the base frequency, with the strength of the harmonic signals decreasing in intensity with increasing harmonic order. For example, a first harmonic signal should have a higher intensity than a third harmonic signal. The harmonic kernel filters may mimic expected harmonic structure of aircraft and/or of other sources of audio signal. Additional harmonic filters may be used to mimic other audio sources such as motor vehicles, trains, animals, etc. Where an audio signal correlates with one of the non-aircraft harmonic filters, the signal is likely to be associated with a non-aircraft source rather than an aircraft source. For example, some harmonic kernel filters may mimic the structure of an audio signal coming from a truck. When a multichannel audio signal correlates to this harmonic filter, the probability that the signal originates from one or more intruder aircraft decreases.

[0072] An optional generating operation **310** generates a feature vector using the preprocessed beamformed signal and the most relevant filter, e.g., the highest correlated harmonic filter. For example, the generating operation **310** may combine the processed signal **318** with the harmonic filter **320** to generate the feature vector **322**. The feature vector **322** generally shows an intensity of the multichannel audio signal at each band 2 Hz wide. The feature vector **322** may be represented as an image (or other computer vision or computer readable format) where various colors (or other elements) within the feature vector **322** represent signal intensity within various bands. For example, the feature vector **322**, shown in greyscale, shows black for no signal, white for a high intensity signal, and varying shades of grey, where lighter grey is a higher intensity signal and darker grey is a lower intensity signal.

[0073] A generating operation **312** generates an estimate that the signal is from an aircraft and directional information by providing the frequency vector to a model. In some implementations, the feature vector **322** may be passed to a binary classifier trained to make an encounter determination. In other implementations, the generating operation **312** may be carried out by, for example, a convolutional neural network. In some implementations, the model used to carry out the generating operation **312** may be DAA model **132**. Once the generating operation **312** has determined that the feature vector **322** is correlated with a signal from an intruder, the DAA system may use the determination to take several actions including, for example, commanding an initial avoidance maneuver, estimating location of the intruder, or creating a track for the intruder.

[0074] FIG. **7** is a flow diagram of example steps for commanding a maneuver or change in flight plan or path based on a multichannel audio signal received by an DAA system, such as one to increase a distance between the aircraft **100** and the intruder **102**, e.g., avoidance maneuver. A receiving operation **402** receives a multichannel audio signal at an aircraft acoustic array. The receiving operation **402** may, in some implementations, include some processing of the multichannel audio signal. For example, the receiving operation **402** may time stamp signals, time align the multichannel audio signal across the channels, convert an analog signal to a digital signal, domain transform the signal, or otherwise process or manipulate the received multichannel audio signal.

[0075] In some implementations, the receiving operation **402** may include processing to compensate for one or more microphones of the array that are not functioning properly. For example the processing may use a variable beamforming approach to process signals from the operating microphones while ignoring signals from microphones that are not operating correctly. For example, the DAA system may "skip" or disregard signals from microphones that are not operating properly and continue with audio detection using functional microphones. The DAA system may identify non-functioning microphones during pre-flight checks of the audio array or by

analyzing whether the signals from the various microphones include expected signals from the engines and propellers of the aircraft **100**. Where the signals do not include such expected signals, the DAA system may assume microphones collecting the signals are not functioning as expected.

[0076] In an operation **404**, the DAA system determines whether the multichannel audio signal is associated with an intruder. In some implementations, the DAA system may first determine whether the signal is directional and whether the signal includes more than the signal expected from the engines and propellers of the aircraft **100**. Where the signal is not directional or includes mainly a signal from the engines of the aircraft **100**, the DAA system may determine that the signal is not associated with an intruder. Where the signal is directional or includes additional signals, the DAA system may further analyze the signal or may immediately command an initial avoidance maneuver.

[0077] Additional analysis of the signal (or initial analysis, where directionality is not determined) may include comparison, such as through cross-correlation or other methods, of the multichannel audio signal to a bank of harmonic filters. In various implementations, the decision of the operation **402** may also be carried out by the DAA model **132**, which may be implemented by a classifier, deep neural network, or other machine learning model. For example, the decision may be made using a random forest trained on frequencies of multichannel audio signals associated with aircraft.

[0078] Where the multichannel audio signal is not associated with an intruder, the method returns to the receiving operation **402**. Where the multichannel audio signal is associated with an intruder, a commanding operation **406** commands an avoidance maneuver, which may be an initial avoidance maneuver or may be an additional maneuver depending on the number of maneuvers that may be needed to avoid the intruder and/or flight path of the intruder. The avoidance maneuver may be an avoidance maneuver that moves the aircraft **100** to a location where collision with another aircraft is statistically less likely. For example, the aircraft **100** may initially descend to a lower altitude to avoid collision, as long as the aircraft **100** is flying above its minimum altitude at the time of the maneuver. In some implementations, the avoidance maneuver may be selected by analyzing flight data to observe where collisions occur. In other implementations, the avoidance maneuver may be generated by the DAA model **132**, which may use the multichannel audio signal characteristics to predict movement of the intruder **102**. Accordingly, the DAA model **132** may select an avoidance maneuver likely to move the aircraft **100** further from the intruder **102**.

[0079] FIG. **8** is a flow diagram of example steps for training a model of an example detection and avoidance system. For example, the steps included in FIG. **8** may be used to train or generate the DAA model **132** described with respect to FIG. **4**. Generally, the steps may be used to generate labeled data sets or to generate a deep neural network using known data. A collecting operation **502** collects acoustic data of intruder aircraft (or other likely intruder sources). The collecting operation **502** may use real-world data, simulated data, or a combination of real-world and simulated data. For example, real-world data may include audio data collected during a position-tracked flight, audio data collected from a ground-based array, or audio files of typical aircraft sounds.

[0080] The collecting operation **502** may use an array substantially similar to the array associated with the aircraft **100**. For example, an array used in the collecting operation **502** may include the same number of microphones **114***a-n* spaced similarly. In one implementation, an array used in the collecting operation **502** is the array of the aircraft **100**, where the aircraft **100** is flown with tracking sensors (e.g., on a GPS tracked flight) and intruder are also flown with similar tracking sensors. In another implementation, the array of the aircraft **100** may be used in the collecting operation in conjunction with a ground-based LiDAR or radar sensor. In yet another implementation, an array substantially similar to the array of the aircraft **100** may be used in the collecting operation **502** as a ground-based array.

[0081] The collecting operation **502** may employ simulated data generated using software simulations, physical simulations, or a combination of simulations. For example, acoustic simulation software may use acoustic data generated by aircraft test flights. In many

implementations, the collecting operation **502** may collect data using multiple methods described above to generate a robust data set for training or generating the DAA model **132**. Further, in some implementations, data generated through use of the DAA system may be used to update and re-train the DAA model **132**.

[0082] A matching operation **504** matches collected acoustic data with known position data for intruder aircraft. The matching operation **504** may include in various implementations, matching ground-based or flight based location data to acoustic data collected at a ground-based array. For example, the matching operation **504** may use time alignment to match ground based LiDAR data, aircraft-based GPS data, or ADS-B data to acoustic data collected at a ground based array during the collecting operation **502**. The matching operation **504** may also include matching ADS-B, GPS, or other positioning data to acoustic data collected at an aircraft mounted array.

[0083] A training operation **506** trains a machine learning model to generate position information based on acoustic signals using the matched acoustic data and position data as labeled observations. The training operation **506** may include generating a deep neural network based on the dataset created by the collecting operation **502** and the matching operation **504**. The training operation **506** may also use the dataset (as labeled observations) to train other types of machine learning models, such as classifiers. In some implementations, the training operation **506** may use the same or similar datasets to generate or train several different types of machine learning models, which may be combined to form the DAA model **132**. The training operation **506** may include multiple types of datasets described above. For example, the training operation **506** may generate a deep neural network using data from a ground based array, an aircraft mounted array, and simulated data.

[0084] As more data is collected, the DAA model **132** may be updated or re-trained. Accordingly, over time, the DAA system may become more accurate in its position estimations of intruder.

[0085] FIG. **9** is a schematic diagram of an example computer system **600** for implementing various embodiments in the examples described herein. A computer system **600** may be used to implement the DAA node **106** (in FIG. **2**) or integrated into one or more components of the aircraft control system **104**. For example, the DAA model **132** may be implemented using one or more of the components of the computer system **600** shown in FIG. **9**. The computer system **600** is used to implement or execute one or more of the components or operations disclosed in FIGS. **1-8**. In FIG. **9**, the computer system **600** may include one or more processing elements **602**, an input/output interface **604**, a display **606**, one or more memory components **608**, a network interface **610**, and one or more external devices **612**. Each of the various components may be in communication with one another through one or more buses, communication networks, such as wired or wireless networks.

[0086] The processing element **602** may be any type of electronic device capable of processing, receiving, and/or transmitting instructions. For example, the processing element **602** may be a central processing unit, microprocessor, processor, or microcontroller. Additionally, it should be noted that some components of the computer **600** may be controlled by a first processor and other components may be controlled by a second processor, where the first and second processors may or may not be in communication with each other.

[0087] The memory components **608** are used by the computer **600** to store instructions for the processing element **602**, as well as store data, such as multichannel audio data **134** and **140** (FIG. **4**) and the like. The memory components **608** may be, for example, magneto-optical storage, read-only memory, random access memory, erasable programmable memory, flash memory, or a combination of one or more types of memory components.

[0088] The display **606** provides visual feedback to a user. Optionally, the display **606** may act as an input element to enable a user to control, manipulate, and calibrate various components of the DAA node **106** or the aircraft control **104** as described in the present disclosure. The display **606** may be a liquid crystal display, plasma display, organic light-emitting diode display, and/or other suitable display. In embodiments where the display **606** is used as an input, the display may include

one or more touch or input sensors, such as capacitive touch sensors, a resistive grid, or the like.

[0089] The I/O interface **604** allows a user to enter data into the computer **600**, as well as provides an input/output for the computer **600** to communicate with other devices or services. The I/O interface **604** can include one or more input buttons, touch pads, and so on.

[0090] The network interface **610** provides communication to and from the computer **600** to other devices. The network interface **610** includes one or more communication protocols, such as, but not limited to WiFi, Ethernet, Bluetooth, and so on. The network interface **610** may also include one or more hardwired components, such as a Universal Serial Bus (USB) cable, or the like. The configuration of the network interface **610** depends on the types of communication desired and may be modified to communicate via Wifi, Bluetooth, and so on.

[0091] The external devices **612** are one or more devices that can be used to provide various inputs to the computing device **600**, e.g., mouse, microphone, keyboard, trackpad, or the like. The external devices **612** may be local or remote and may vary as desired. In some examples, the external devices **612** may also include one or more additional sensors.

[0092] The foregoing description has a broad application. For example, while examples disclosed herein may focus on central communication system, it should be appreciated that the concepts disclosed herein may equally apply to other systems, such as a distributed, central or decentralized system, or a cloud system. For example, some components may reside on a server in a client/server system, on a user mobile device, or on any device on the network and operate in a decentralized manner. One or more components of the systems may also reside in a controller virtual machine (VM) or a hypervisor in a VM computing environment. Accordingly, the disclosure is meant only to provide examples of various systems and methods and is not intended to suggest that the scope of the disclosure, including the claims, is limited to these examples.

[0093] The technology described herein may be implemented as logical operations and/or modules in one or more systems. The logical operations may be implemented as a sequence of processor-implemented steps directed by software programs executing in one or more computer systems and as interconnected machine or circuit modules within one or more computer systems, or as a combination of both. Likewise, the descriptions of various component modules may be provided in terms of operations executed or effected by the modules. The resulting implementation is a matter of choice, dependent on the performance requirements of the underlying system implementing the described technology. Accordingly, the logical operations making up the embodiments of the technology described herein are referred to variously as operations, steps, objects, or modules. Furthermore, it should be understood that logical operations may be performed in any order, unless explicitly claimed otherwise or a specific order is inherently necessitated by the claim language.

[0094] In some implementations, articles of manufacture are provided as computer program products that cause the instantiation of operations on a computer system to implement the procedural operations. One implementation of a computer program product provides a non-transitory computer program storage medium readable by a computer system and encoding a computer program. It should further be understood that the described technology may be employed in special purpose devices independent of a personal computer.

[0095] The above specification, examples and data provide a complete description of the structure and use of exemplary embodiments of the invention as defined in the claims. Although various embodiments of the claimed invention have been described above with a certain degree of particularity, or with reference to one or more individual embodiments, it is appreciated that numerous alterations to the disclosed embodiments without departing from the spirit or scope of the claimed invention may be possible. Other embodiments are therefore contemplated. It is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative only of particular embodiments and not limiting. Changes in detail or structure may be made without departing from the basic elements of the invention as defined in the following claims.

Claims

1. A method comprising: receiving a first audio signal at audio sensors of an aircraft at a first position of the aircraft; analyzing, by a detection and avoidance (DAA) model at computing resources associated with the aircraft, the first audio signal to determine a first signal source associated with the first audio signal, wherein the DAA model is a machine learned model trained on acoustic data from known signal sources detectable during flight; generating, by the DAA model, a position and velocity estimation of the first signal source associated with the first audio signal; classifying, by the DAA model, the first signal source as an air-based signal source based on the position and velocity estimation of the first signal source; and generating, by the DAA model, a modification of a flight characteristic of the aircraft based on the classification of the first signal source and the position and velocity estimation of the first signal source.

2. The method of claim 1, further comprising: classifying, by the DAA, a second signal source associated with the first audio signal as an air-based audio source based on a position and velocity estimation of the second signal source; and generating, by the DAA, a second modification of the flight characteristic of the aircraft based on the classification of the first signal source and the second signal source and based on the position and velocity estimation of the first signal source and the second signal source, wherein the second modification of the flight characteristic may be configured to cause the aircraft to maintain a distance between the aircraft and the first signal source and second signal source.

3. The method of claim 1, wherein analyzing the first audio signal comprises distinguishing a broadband audio signal, non-directional audio signal, and near-field audio signal to identify the first signal source associated with the first audio signal.

4. The method of claim 1, wherein generating the position and velocity estimation of the first signal source comprises determining a directionality of a signal relative to the aircraft associated with the first signal source.

5. The method of claim 4, wherein determining a directionality of the signal associated with the first signal source comprises generating a probabilistic estimation of the azimuth angle and elevation of the signal associated with the first signal source relative to the aircraft.

6. The method of claim 1, wherein generating the position and velocity estimation of the first signal source comprises: generating a plurality of position estimations of the first signal source based on the first audio signal; receiving a second audio signal at audio sensors of the aircraft at a second position of the aircraft; and analyzing the plurality of position estimations based on the second audio signal to converge on a single position estimation of the first signal source.

7. The method of claim 6, wherein generating the plurality of position estimations of the first signal source comprises: receiving, by the DAA model, a terrain map comprising a topographical representation of the location of the plurality of position estimations; and generating the plurality of position estimations constrained by the terrain map.

8. The method of claim 1, wherein classifying the first signal source as an air-based signal source comprises: receiving, by the DAA model, a terrain map comprising a topographical representation of the location of the position estimation of the first signal source; and determining that the position estimation of the first signal source is positioned above a threshold terrain line based on the terrain map, such that the position estimation of the first signal source is not positioned on the ground.

9. The method of claim 1, wherein classifying the first signal source as an air-based signal source further comprises generating a semantic classification of the first signal source based on a comparison of a signal associated with the first signal source with audio signals associated with known air-based signal sources.

10. The method of claim 9, wherein generating the semantic classification of the first signal source comprises generating the semantic classification via a machine learning model trained on audio

frequencies of multichannel audio signals associated with known air-based signal sources.

11. The method of claim 9, wherein generating the semantic classification of the first signal source further comprises generating a probabilistic confidence interval associated with the semantic classification, and wherein generating the modification of the flight characteristic of the aircraft further comprises generating the modification of the flight characteristic based on the probabilistic confidence interval associated with the semantic classification of the first signal source.

12. The method of claim 1, wherein generating the position and velocity estimation of the first signal source further comprises generating a probabilistic confidence interval associated with the position and velocity estimation of the first signal source, and wherein generating the modification of the flight characteristic of the aircraft further comprises generating the for modification of the flight characteristic based on the probabilistic confidence interval associated with the position and velocity estimation of the first signal source.

13. A system comprising: an aircraft; and a detection and avoidance (DAA) model at computing resources associated with the aircraft configured by instructions to perform operations comprising: receiving a first audio signal at audio sensors of an aircraft at a first position of the aircraft; analyzing the first audio signal to determine a first signal source associated with the first audio signal; generating a position and velocity estimation of the first signal source associated with the first audio signal; classifying the first signal source as an air-based signal source based on the position and velocity estimation of the first signal source; and generating a modification of a flight characteristic of the aircraft based on the classification of the first signal source and the position and velocity estimation of the first signal source.

14. The system of claim 13, wherein the DAA is further configured by instructions to perform operations comprising: classifying a second signal source associated with the first audio signal as an air-based audio source based on a position and velocity estimation of the second signal source; and generating a second modification of the flight characteristic of the aircraft based on the classification of the first signal source and the second signal source and based on the position and velocity estimation of the first signal source and the second signal source, wherein the second modification of the flight characteristic may be configured to cause the aircraft to maintain a distance between the aircraft and the first signal source and second signal source.

15. The system of claim 13, wherein generating the position and velocity estimation of the first signal source comprises determining a directionality of a signal associated with the first signal source.

16. The system of claim 15, wherein determining a directionality of the signal associated with the first signal source comprises generating a probabilistic estimation of the azimuth angle and elevation of the signal associated with the first signal source relative to the aircraft.

17. The system of claim 13, wherein generating the position and velocity estimation of the first signal source comprises: generating a plurality of position estimations of the first signal source based on the first audio signal; receiving a second audio signal at audio sensors of the aircraft at a second position of the aircraft; and analyzing the plurality of position estimations based on the second audio signal to converge on a single position estimation of the first signal source.

18. The system of claim 13, wherein generating the plurality of position estimations of the first signal source comprises: receiving, by the DAA model, a terrain map comprising a topographical representation of the location of the plurality of position estimations; and generating the plurality of position estimations constrained by the terrain map.

19. The system of claim 13, wherein classifying the first signal source as an air-based signal source comprises: receiving, by the DAA model, a terrain map comprising a topographical representation of the location of the position estimation of the first signal source; and determining that the position estimation of the first signal source is positioned above a threshold terrain line based on the terrain map, such that the position estimation of the first signal source is not positioned on the ground.

20. The system of claim 13, wherein classifying the first signal source as an air-based signal source

further comprises generating a semantic classification of the first signal source based on a comparison of a signal associated with the first signal source with audio signals associated with known air-based signal sources.

21. The method of claim 1, wherein the modification of the flight characteristic of the aircraft comprises at least one of a change in the roll, pitch, yaw, elevation, or velocity of the aircraft.