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(54) **SYSTEMS AND METHODS FOR COLLISION AVOIDANCE IN UNMANNED AERIAL VEHICLES**

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G01S 13/00 (2006.01)

(52) **U.S. Cl.** **342/63**; 342/59

(58) **Field of Classification Search** 342/59, 342/61–72

See application file for complete search history.

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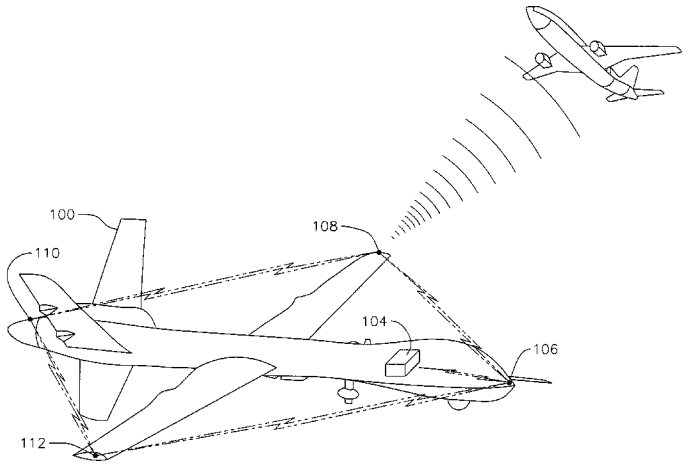
(74) *Attorney, Agent, or Firm* — Christie, Parker & Hale, LLP

(57) **ABSTRACT**

Systems and methods for collision avoidance in unmanned aerial vehicles are provided. In one embodiment, the invention relates to a method for collision avoidance system for an unmanned aerial vehicle (UAV), the method including scanning for objects within a preselected range of the UAV using a plurality of phased array radar sensors, receiving scan information from each of the plurality of phased array radar sensors, wherein the scan information includes information indicative of objects detected within the preselected range of the UAV, determining maneuver information including whether to change a flight path of the UAV based on the scan information, and sending the maneuver information to a flight control circuitry of the UAV.

35 Claims, 9 Drawing Sheets



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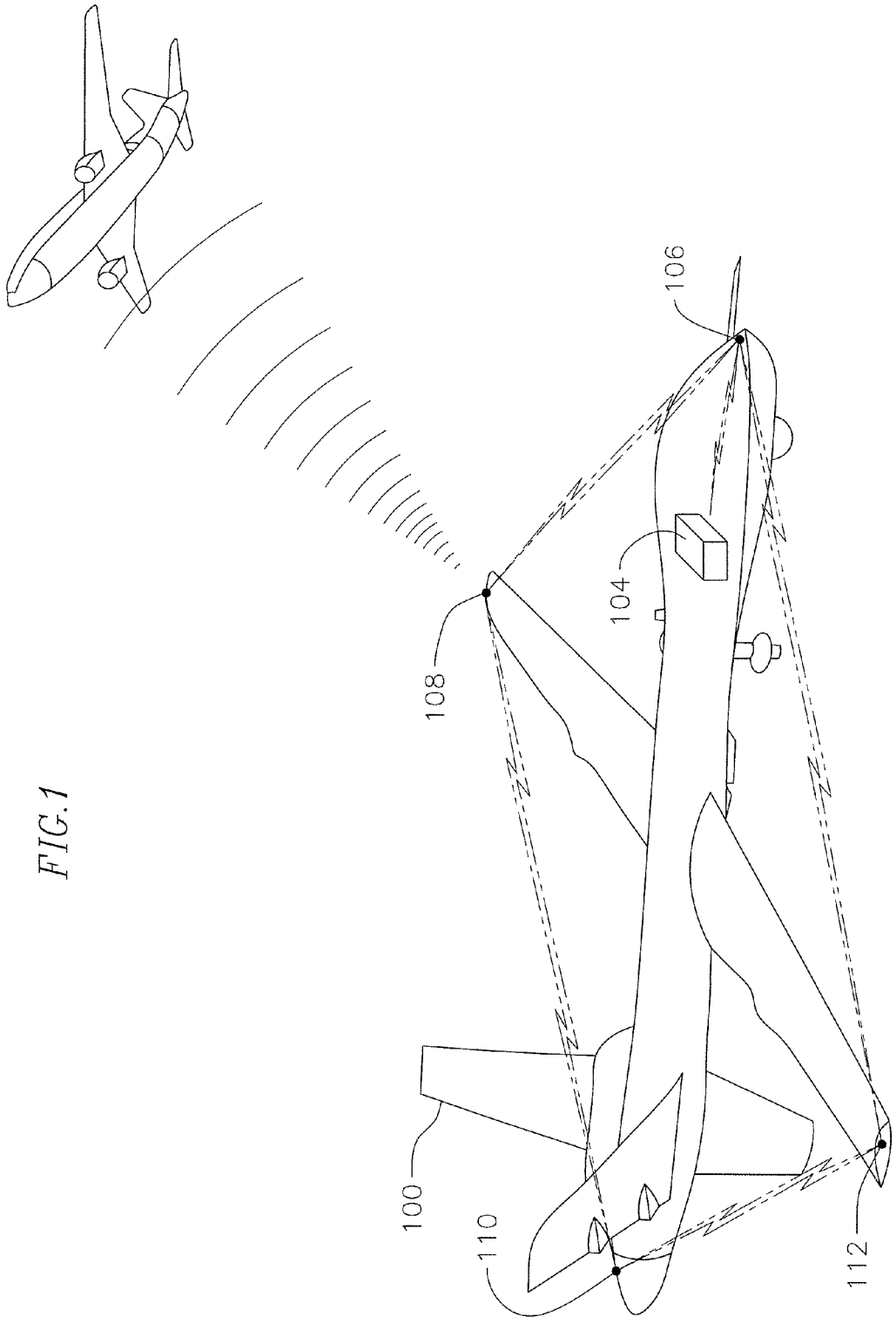


FIG. 1

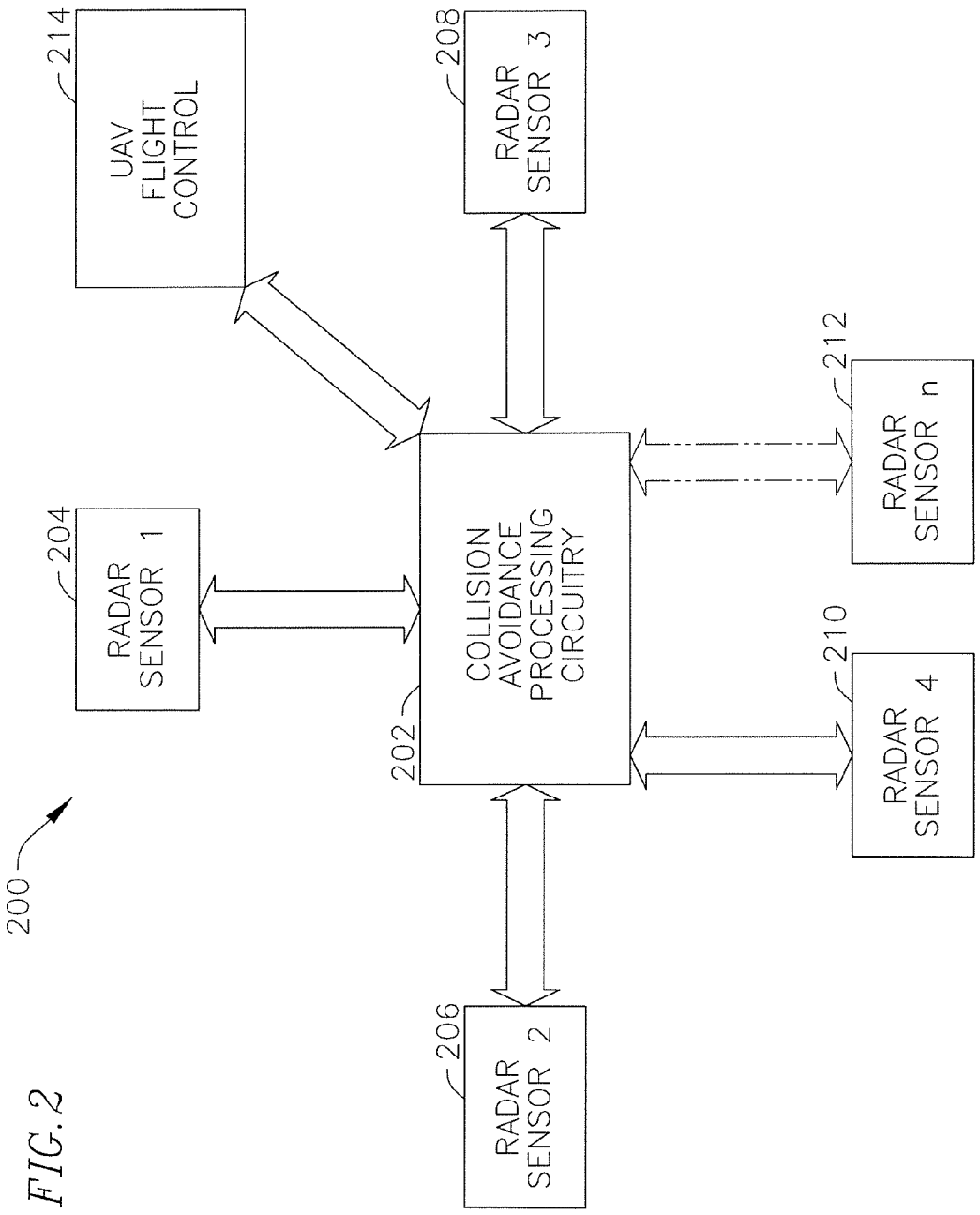

200
214
UAV FLIGHT CONTROL
208
RADAR SENSOR 3
212
RADAR SENSOR n
204
RADAR SENSOR 1
COLLISION AVOIDANCE PROCESSING CIRCUITRY
202
210
RADAR SENSOR 4
206
RADAR SENSOR 2

FIG. 2

FIG. 3

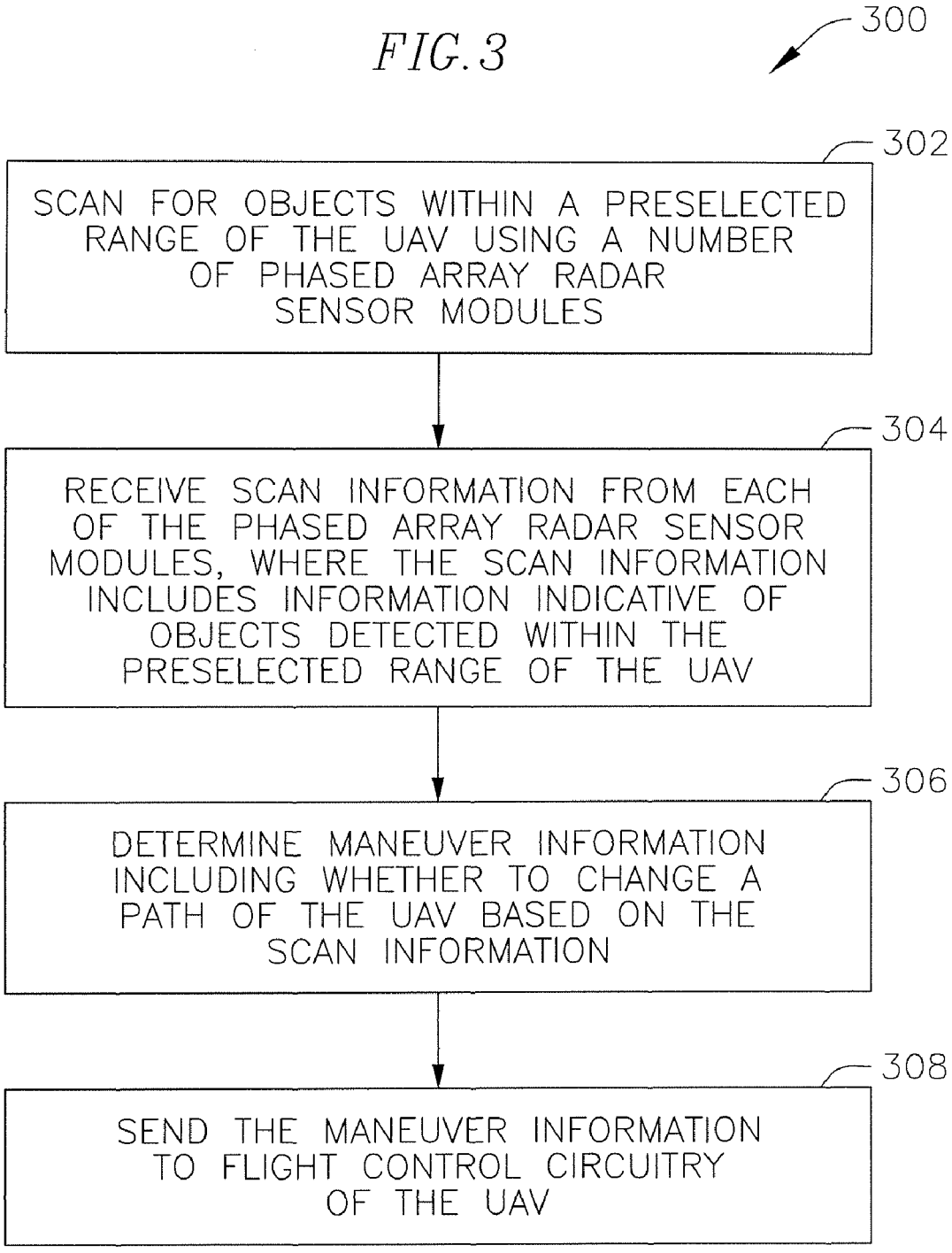

300
302
SCAN FOR OBJECTS WITHIN A PRESELECTED RANGE OF THE UAV USING A NUMBER OF PHASED ARRAY RADAR SENSOR MODULES
304
RECEIVE SCAN INFORMATION FROM EACH OF THE PHASED ARRAY RADAR SENSOR MODULES, WHERE THE SCAN INFORMATION INCLUDES INFORMATION INDICATIVE OF OBJECTS DETECTED WITHIN THE PRESELECTED RANGE OF THE UAV
306
DETERMINE MANEUVER INFORMATION INCLUDING WHETHER TO CHANGE A PATH OF THE UAV BASED ON THE SCAN INFORMATION
308
SEND THE MANEUVER INFORMATION TO FLIGHT CONTROL CIRCUITRY OF THE UAV

FIG. 4

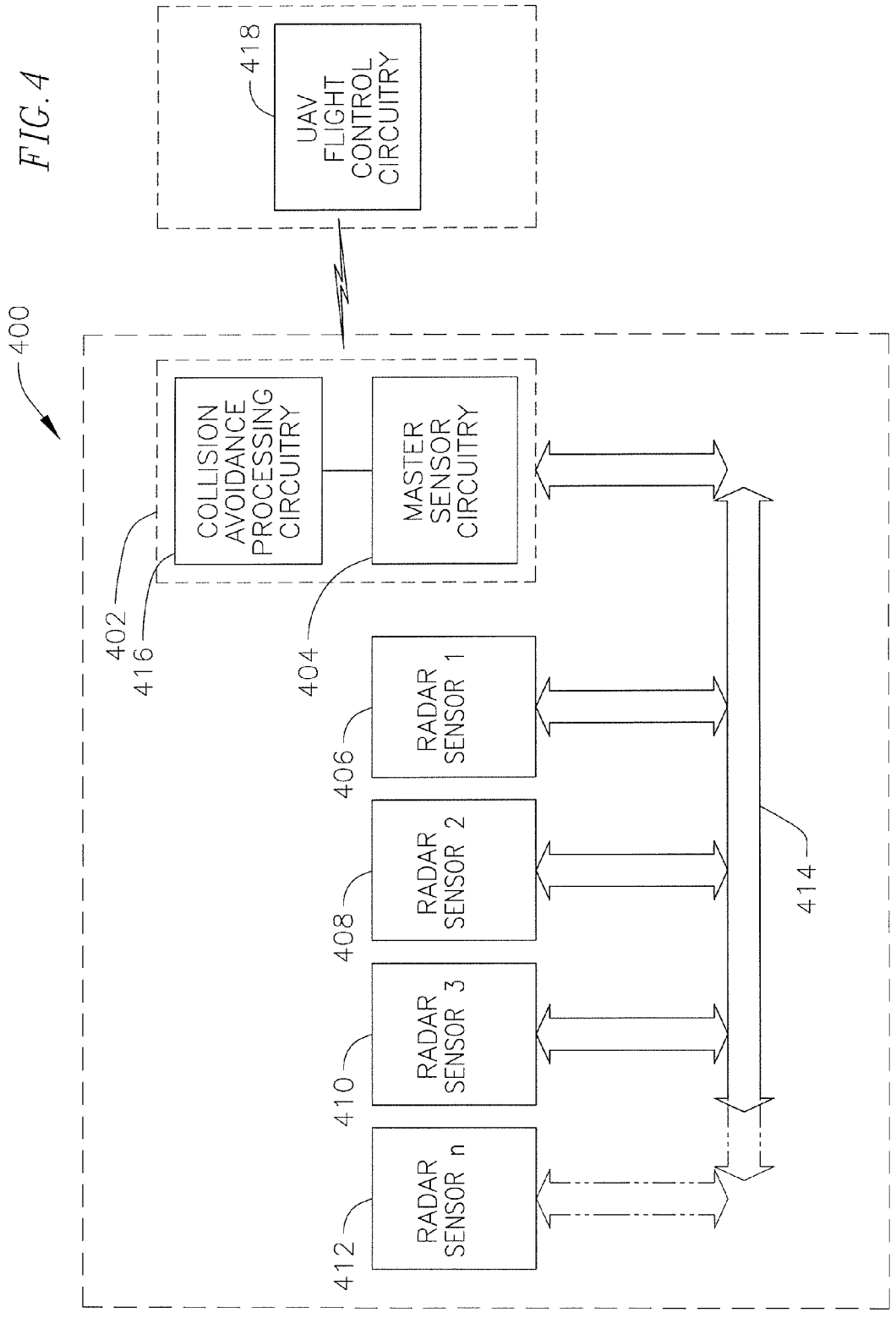
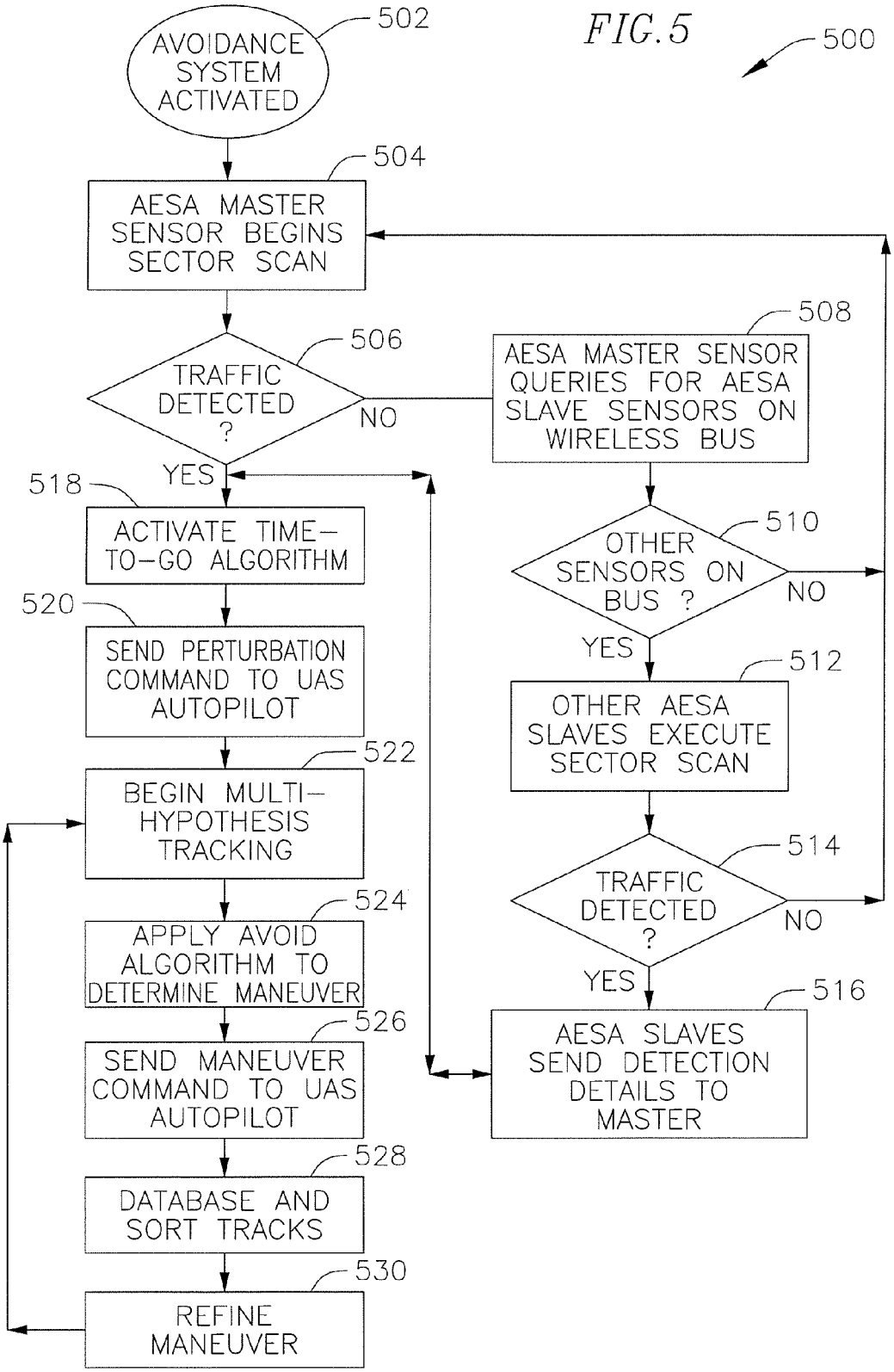

400
418
UAV FLIGHT CONTROL CIRCUITRY
COLLISION AVOIDANCE PROCESSING CIRCUITRY
MASTER SENSOR CIRCUITRY
402
416
404
RADAR SENSOR 1
406
RADAR SENSOR 2
408
RADAR SENSOR 3
410
RADAR SENSOR n
412
414

FIG. 5


500
502
AVOIDANCE SYSTEM ACTIVATED
504
AESA MASTER SENSOR BEGINS SECTOR SCAN
506
TRAFFIC DETECTED ?
NO
YES
508
AESA MASTER SENSOR QUERIES FOR AESA SLAVE SENSORS ON WIRELESS BUS
510
OTHER SENSORS ON BUS ?
NO
YES
512
OTHER AESA SLAVES EXECUTE SECTOR SCAN
514
TRAFFIC DETECTED ?
NO
YES
516
AESA SLAVES SEND DETECTION DETAILS TO MASTER
518
ACTIVATE TIME-TO-GO ALGORITHM
520
SEND PERTURBATION COMMAND TO UAS AUTOPILOT
522
BEGIN MULTI-HYPOTHESIS TRACKING
524
APPLY AVOID ALGORITHM TO DETERMINE MANEUVER
526
SEND MANEUVER COMMAND TO UAS AUTOPILOT
528
DATABASE AND SORT TRACKS
530
REFINE MANEUVER

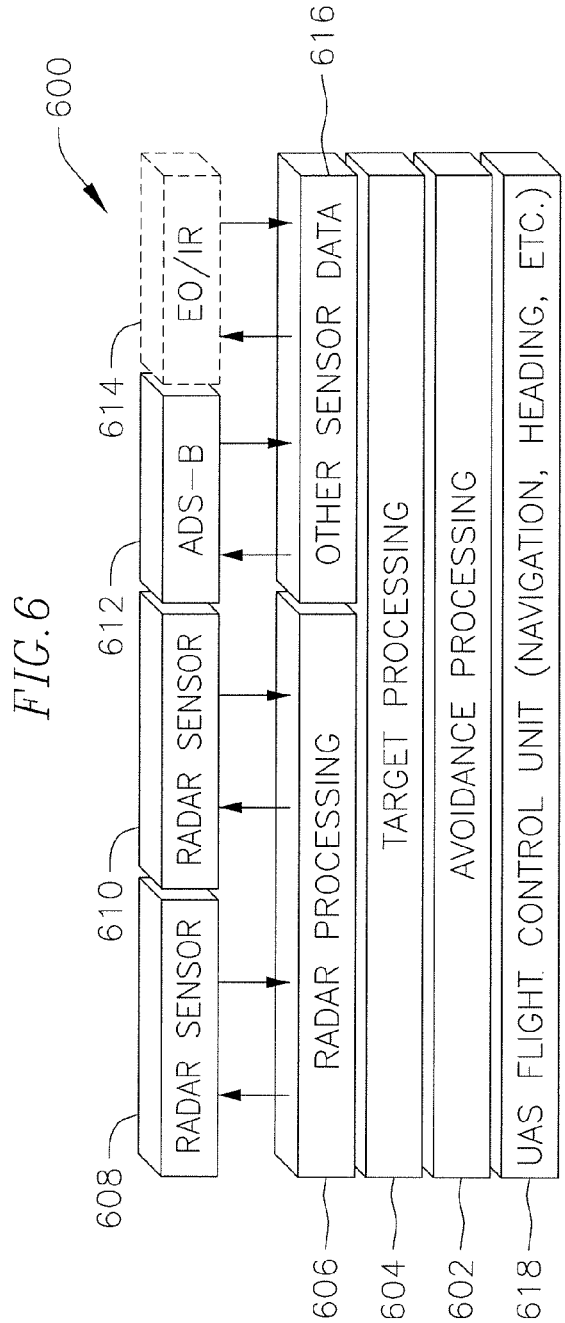

600
608
RADAR SENSOR
610
RADAR SENSOR
612
ADS-B
614
EO/IR
616
OTHER SENSOR DATA
RADAR PROCESSING
606
TARGET PROCESSING
604
AVOIDANCE PROCESSING
602
UAS FLIGHT CONTROL UNIT (NAVIGATION, HEADING, ETC.)
618

FIG. 6

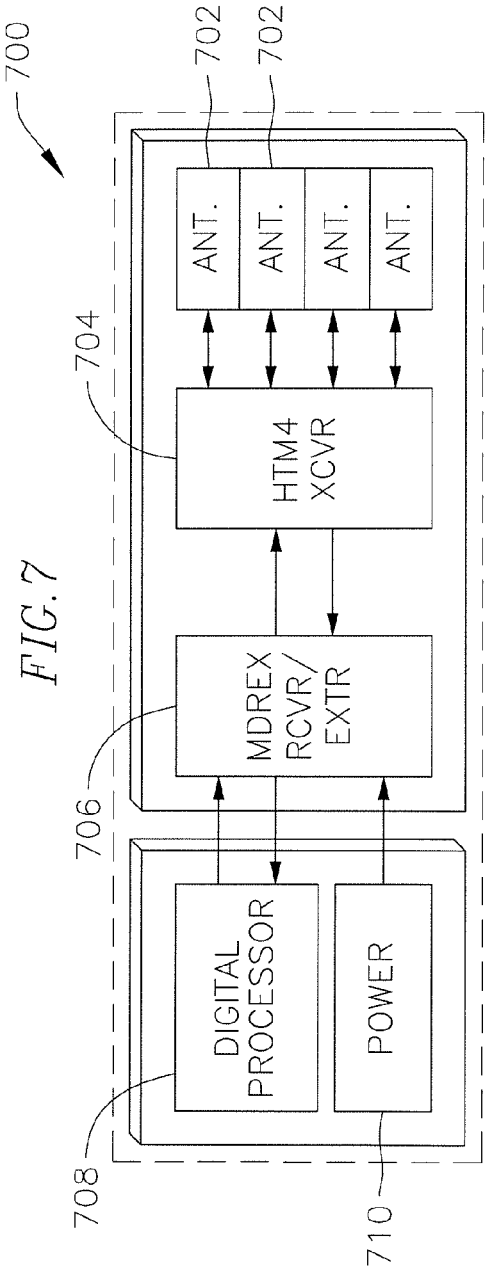

700
702
ANT.
ANT.
ANT.
ANT.
704
HTM4 XCVR
706
MDREX RCVR/ EXTR
708
DIGITAL PROCESSOR
POWER
710

FIG. 7

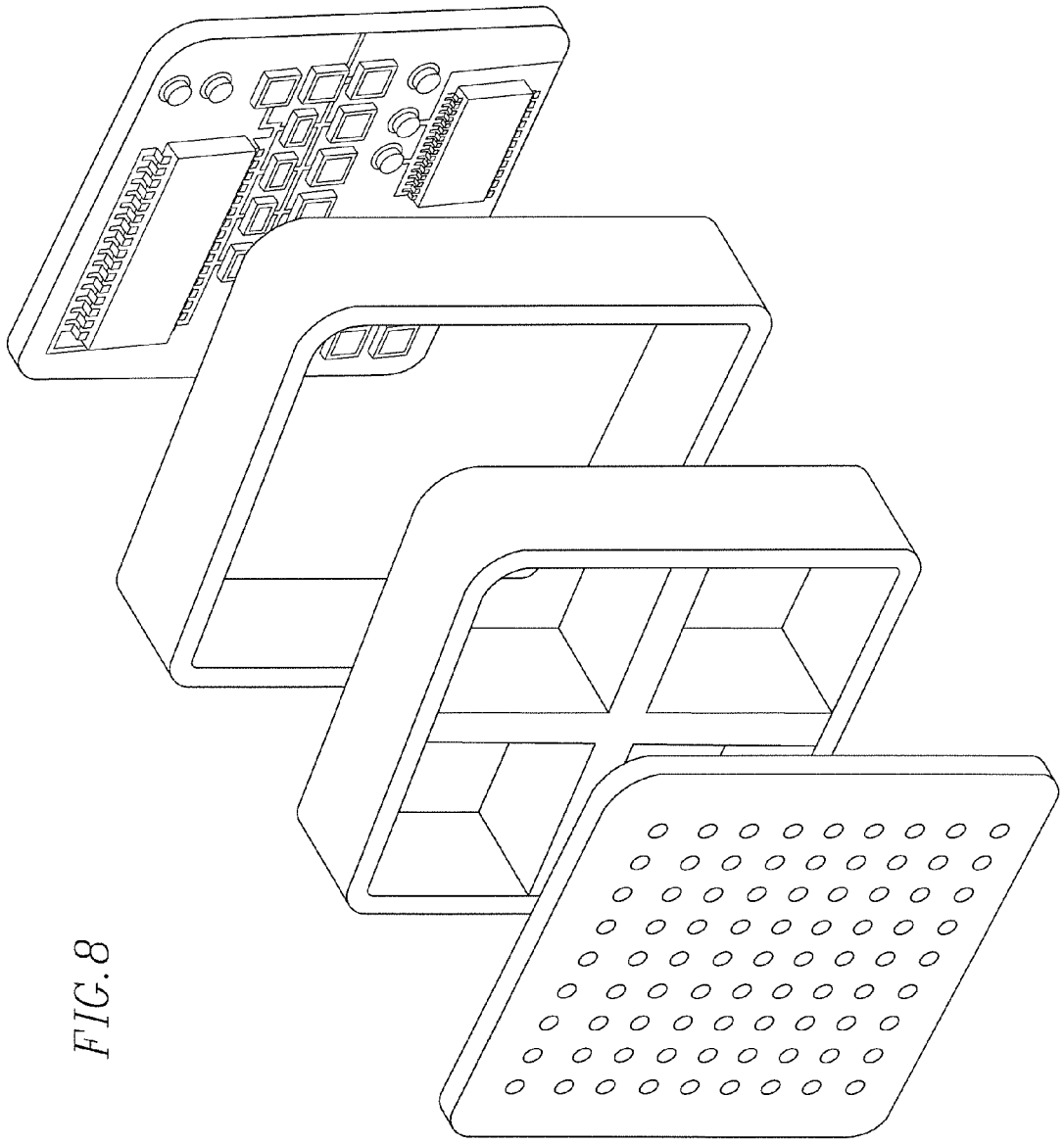
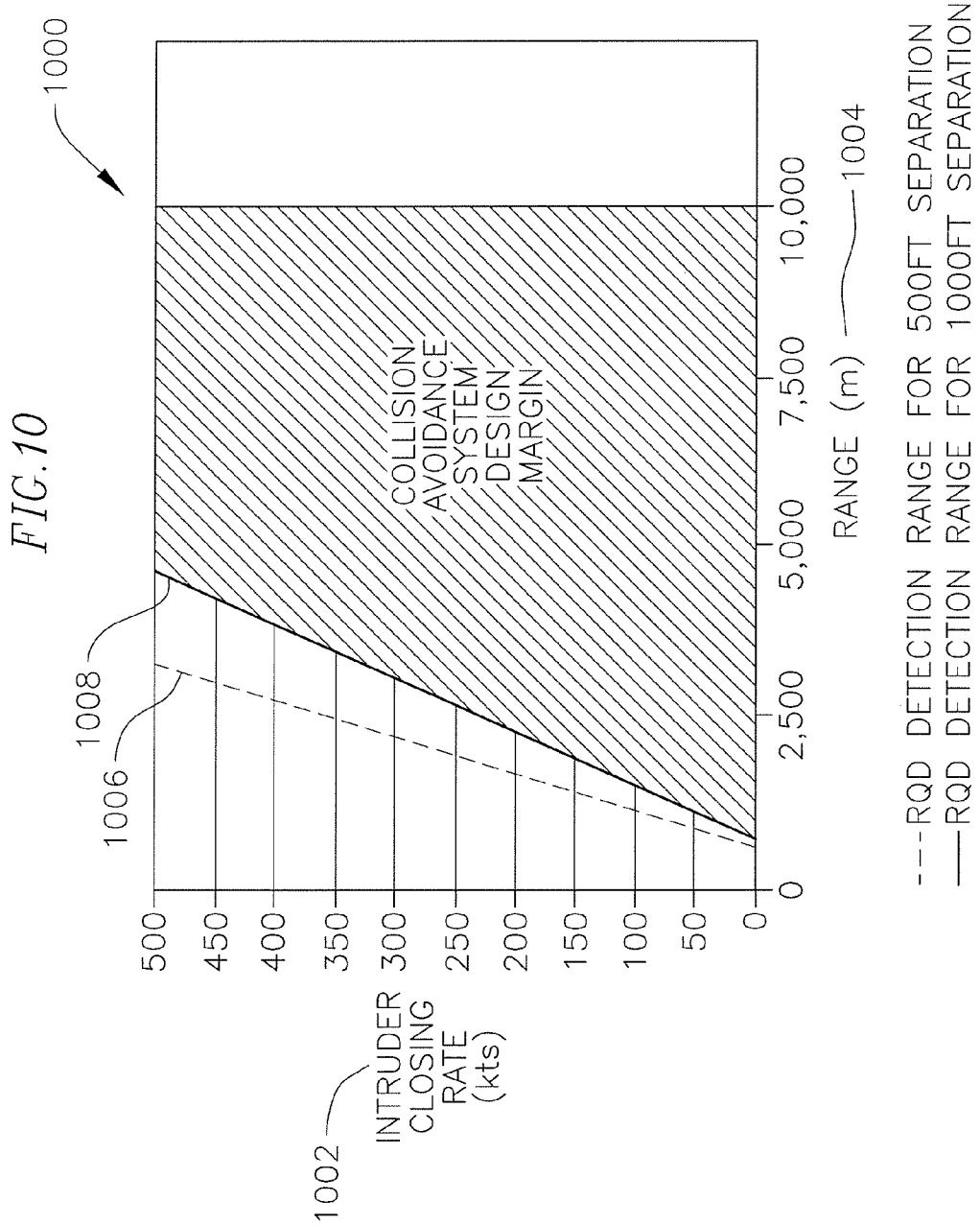


FIG. 8

FIG. 9

PARAMETER	FIRE SCOUT
SYSTEM POWER/WT	284 W/11lb
CPU POWER/WT	30 W/2lb
μPATCH POWER/WT	38 W/4lb
μPATCH SIZE	3in X 3in X 2in
#μPATCH MODULES	4–6*
CABLING	2lb
POWER CONVERSION	26 W/4lb
μPATCH RF POWER	160 Wpeak
μPATCH RF BAND	X–BAND
RECEIVER BW	10 MHz
NOISE FIGURE	2 dB
NOMINAL PW	10 μSEC
PRF RANGE	1–15 kHz
DUTY CYCLE (MAX)	20%
COOLING	AIR

FIG. 10


1000
1008
1006
COLLISION AVOIDANCE SYSTEM DESIGN MARGIN
500
450
400
350
300
250
200
150
100
50
0
1002
INTRUDER CLOSING RATE (kts)
0
2,500
5,000
7,500
10,000
RANGE (m)
1004
---RQD DETECTION RANGE FOR 500FT SEPARATION
——RQD DETECTION RANGE FOR 1000FT SEPARATION

SYSTEMS AND METHODS FOR COLLISION AVOIDANCE IN UNMANNED AERIAL VEHICLES

FIELD

The present invention relates generally to collision avoidance systems, and more specifically, to systems and methods for collision avoidance in unmanned aerial vehicles.

BACKGROUND

Unmanned aerial vehicles are often useful in various military applications. At times, however, it may be preferred that UAVs are used within the national airspace system of the United States or in other airspaces frequented by commercial or other non-military aircraft. Each of these airspaces may be governed by various regulatory agencies that promulgate rules for maintaining safety within their respective airspace. For UAVs to travel in such airspaces, the regulatory agencies may require that the UAVs be certified for travel among the commercial or other non-military aircraft common to their respective airspaces. As such, UAVs which meet the safety requirements of one or more of these regulatory agencies would be desirable.

SUMMARY

Aspects of the invention relate to systems and methods for collision avoidance in unmanned aerial vehicles. In one embodiment, the invention relates to a collision avoidance system for an unmanned aerial vehicle (UAV), the system comprising a flight control circuitry configured to control a flight path of the UAV, a plurality of radar sensors configured to scan for objects within a preselected range of the UAV and to store scan information indicative of the objects detected within the preselected range, and a processing circuitry coupled to the flight control circuitry and configured to receive the scan information from each of the plurality of radar sensors, determine maneuver information comprising whether to change the flight path of the UAV based on the scan information, and send the maneuver information to the flight control circuitry, wherein each of the plurality of radar sensors is configured to operate as a phased array.

In another embodiment, the invention relates to a method for collision avoidance system for an unmanned aerial vehicle (UAV), the method including scanning for objects within a preselected range of the UAV using a plurality of phased array radar sensors, receiving scan information from each of the plurality of phased array radar sensors, wherein the scan information includes information indicative of objects detected within the preselected range of the UAV, determining maneuver information including whether to change a flight path of the UAV based on the scan information, and sending the maneuver information to a flight control circuitry of the UAV.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of an unmanned aerial vehicle (UAV) in the vicinity of a second airship, the UAV including a collision avoidance system having central processing circuitry in wireless communication with a number of distributed radar sensors in accordance with one embodiment of the invention.

FIG. **2** is a schematic block diagram of a collision avoidance system for a UAV including central processing circuitry in wireless communication with a number of radar sensors configured in a network having a star topology in accordance with one embodiment of the invention.

FIG. **3** is a flowchart of a process for operating a collision avoidance system for a UAV in accordance with one embodiment of the invention.

FIG. **4** is a schematic block diagram of a collision avoidance system for a UAV including central processing circuitry having an integrated master radar sensor in wireless communication with a number of radar sensors configured in a network having a bus topology in accordance with one embodiment of the invention.

FIG. **5** is a flowchart of another process for operating a collision avoidance system for a UAV in accordance with one embodiment of the invention.

FIG. **6** is a schematic block diagram of a collision avoidance system for a UAV including various processing circuitry in communication a variety of sensor modules in accordance with one embodiment of the invention.

FIG. **7** is a schematic block diagram of a radar sensor module in accordance with one embodiment of the invention.

FIG. **8** is a perspective exploded view of an X-Band radar transceiver in accordance with one embodiment of the invention.

FIG. **9** is a table illustrating performance parameters for a collision avoidance system for a Fire Scout UAV in accordance with one embodiment of the invention.

FIG. **10** is a graph of intruder closing speed versus range that generally illustrates baseline transmit power and track revisit rates to ensure safe UAV maneuvering rates to meet preselected safety requirements in accordance with one embodiment of the invention.

DETAILED DESCRIPTION

Referring now to the drawings, embodiments of collision avoidance systems for unmanned aerial vehicles include processing circuitry configured to receive information from one or more radar sensors located at various positions along the body of a UAV, to determine whether a maneuver is necessary to avoid other aircraft based on the information received from the radar sensors or other sensors, and to send maneuver instructions to a flight control circuitry of the UAV. Embodiments of the radar sensors can include one or more antennas, a transceiver coupled to the antennas, sensor processing circuitry and wireless communication circuitry. The radar sensors can be configured to operate as a phased array radar and perform sector scans on command to detect objects and characteristics of their movement within a preselected range.

In some embodiments, the radar sensors are coupled in a network having a bus topology having a master sensor and one or more slave sensors. In some embodiments, the radar sensors are coupled in a network having a star topology. In other embodiments, the radar sensors are coupled in a network having a other network topologies. In some embodiments, the radar sensors are coupled using wired connections rather than wireless connections.

FIG. **1** is a perspective view of an unmanned aerial vehicle (UAV) **100** in the vicinity of a second airship **102**, where the UAV includes a collision avoidance system having central processing circuitry **104** and a number of distributed radar sensors (**106**, **108**, **110**, **112**) in wireless communication with each other in accordance with one embodiment of the invention. The central processing circuitry **104** is positioned in the fuselage of the UAV and is coupled to the flight control circuitry (e.g., UAV autopilot circuitry). In other embodiments, the central processing circuitry **104** can be located in

other areas of the UAV. The four radar sensors (**106**, **108**, **110**, **112**) are positioned at various extremities of the UAV including the ends of the wings (**108**, **112**), the nose **106** and the tail end **110**. In other embodiments, more than or less than four radar sensors can be used. In other embodiments, the radar sensors can be positioned at different locations along the body of the UAV.

In operation, the central processing circuitry **104** instructs the radar sensors to perform sector scans. Based on the information provided by the radar sensors, the central processing circuitry determines whether the UAV needs to execute a maneuver to change course and thereby avoid other aircraft detected in the sector scan. The central processing circuitry **104** sends instructions to the flight control circuitry in accordance with the maneuver determination. The radar sensors can be phased array radars configured to detect objects within a preselected range of the UAV. In one embodiment, the preselected range is dependent on the velocity of the UAV.

In FIG. **1**, the body style of the UAV is a particular fixed-wing type body. In other embodiments, UAVs with other body styles can be used and the radar sensors can be positioned accordingly. In the embodiment illustrated in FIG. **1**, the radar sensors and central processing circuitry communicate wirelessly with each using any of the IEEE 802.11, Bluetooth or other Common Data Link high speed wireless communication protocols.

FIG. **2** is a schematic block diagram of a collision avoidance system **200** for a UAV including central processing circuitry **202** in wireless communication with a number of radar sensors (**204**, **206**, **208**, **210**, **212**) configured in a network having a star topology in accordance with one embodiment of the invention. The central processing circuitry **202** is also coupled to, or in wireless communication with, flight control circuitry **214** of the UAV.

In operation, the central processing circuitry **202**, which can also be referred to as collision avoidance processing circuitry, can accumulate and store detection information from each of the radar sensors (**204**, **206**, **208**, **210**, **212**). The central processing circuitry **202** can also control a scan sequence for the radar sensors. Based on the information obtained from the radar sensors, the central processing circuitry **202** determines whether the UAV needs to execute a maneuver to change course and thereby avoid other aircraft detected in the sector scan. The central processing circuitry sends information to a flight control circuitry **214** in accordance with the maneuver determination. The information sent to the flight control circuitry **214** can include maneuver commands and/or tracking database information. The central processing circuitry **202** can perform scan timing, radar sensor data processing, and track development and avoidance algorithms.

Additional sensors can be added to the network up to the nth radar sensor **212**. In several embodiments, the sensors are "plug and play" sensors that can be added or removed from the network with relative ease and minimal reconfiguration of the network. In several embodiments, all of the sensors share information including information on objects detected, objects being tracked, and/or other detection information collected by the sensors. In the collision avoidance system illustrated in FIG. **2**, five radar sensors are used. In other embodiments, more than or less than five radar sensors can be used.

FIG. **3** is a flowchart of a process **300** for operating a collision avoidance system for a UAV in accordance with one embodiment of the invention. In particular embodiments, the process **300** can be used in conjunction with the collision avoidance systems of FIGS. **1**, **2**, and **4**. The process scans (**302**) for objects within a preselected range of the UAV using a number of phased array radar sensors. The process then receives (**304**) scan information from each of the phased array radar sensors, where the scan information includes information indicative of objects detected within the preselected range of the UAV. The information can also include characteristics of the object such as size, speed, heading, and/or other similar information.

The process determines (**306**) maneuver information including whether to change a flight path of the UAV based on the scan information. The process then sends (**308**) the maneuver information to a flight control circuitry of the UAV.

In several embodiments, the process executes one or more collision avoidance algorithms and/or tracking algorithms in determining the maneuver information. The tracking algorithms can use target dynamics and an interactive multiple model approach to maintain robust tracks. In some embodiments, for example, tracks derived from radar sensors can be combined with tracks derived from other sensors such as an automatic dependent surveillance-broadcast/traffic information services-broadcast type sensor (ADS-B/TIS-B) and optionally with additional sources of situational data such as from the UAV's electro-optical/infra-red sensors (EO/IR). In several embodiments, the process can propagate forward tracks in time to assess, detect, and prioritize potential collisions. The process can consider the kinematic capabilities of the UAV when assessing collision situations and computing avoidance maneuvers. In some embodiments, the process can use multiple hypothesis tracking (MHT) technology from Raytheon Corporation of Waltham, Mass. to provide real-time situational awareness of the airspace around the UAV.

In one embodiment, the process can perform the sequence of actions in any order. In another embodiment, the process can skip one or more of the actions. In other embodiments, one of more of the actions are performed simultaneously. In some embodiments, additional actions can be performed.

FIG. **4** is a schematic block diagram of a collision avoidance system **400** for a UAV including central processing circuitry **402** having an integrated master radar sensor **404** in wireless communication with a number of radar sensors (**406**, **408**, **410**, **412**) configured in a network having a bus topology in accordance with one embodiment of the invention. The wireless network of radar sensors includes the master sensor **404** wirelessly coupled to a first slave sensor **406**, a second slave sensor **408**, a third slave sensor **410** and an nth slave sensor **412** by a shared wireless bus **414**.

In operation, the central processing circuitry **402**, including collision avoidance processing circuitry **416**, can accumulate and store detection information from each of the slave sensors (**406**, **408**, **410**, **412**) and the master sensor **404**. The master sensor **404** can control a scan sequence for the slave sensors. Based on the information obtained from the radar sensors, the central processing circuitry **402** determines whether the UAV needs to execute a maneuver to change course and thereby avoid other aircraft detected in the sector scan. The central processing circuitry sends information to a flight control circuitry **418** in accordance with that determination. The information sent to the flight control circuitry **418** can include maneuver commands and/or tracking database information.

Additional sensors can be added to the network up to the nth radar sensor **412**. In several embodiments, the sensors are "plug and play" sensors that can be added or removed from the network with relative ease and minimal reconfiguration of the network. In several embodiments, all of the sensors share information including information on objects detected, objects being tracked, and/or other detection information collected by the sensors. In the collision avoidance system illus-

trated in FIG. **4**, four slave radar sensors are used. In other embodiments, more than or less than four slave radar sensors can be used.

FIG. **5** is a flowchart of another process **500** for operating a collision avoidance system for a UAV in accordance with one embodiment of the invention. In particular embodiments, the process **500** can be used in conjunction with the collision avoidance systems of FIGS. **1**, **2**, and **4**. The process begins by activating (**502**) the collision avoidance system. The process then instructs the master sensor circuitry, which can also be referred to as the active electronically scanned array (AESA) master sensor, to perform (**504**) a sector scan. The process determines (**506**) whether traffic was detected by the master sensor circuitry. If no traffic was detected by the master sensor, the process instructs the master sensor to query (**508**) for slave sensors on the wireless bus.

The process then determines (**510**) whether there are other sensors on the wireless bus. If there are no additional sensors, then the process returns to instructing the master sensor to perform (**504**) the sector scan. If there are other sensors (e.g., other slave sensors), then each of the slave sensors performs (**512**) a sector scan. The process determines (**514**) whether traffic, in the form of airships or other objects within a preselected range, was detected by any of the sensors. If no traffic was detected, then the process returns to instructing the master to perform (**504**) the sector scan. If traffic was detected, then the slave sensors send (**516**) the detection information to the master sensor and the process then activates (**518**) a time-to-go algorithm.

Returning now to whether traffic was detected (**506**) at any sensor. If the traffic was detected, then the process activates (**518**) the time-to-go algorithm. A time-to-go algorithm is an optional method to begin perturbing the flight path of the UAV to maintain or increase time before the unaltered UAV flight path results in a collision (time-to-go) and until a multiple hypothesis tracking algorithm has processed enough data to instruct the UAV with the best possible flight path alteration. During the time-to-go algorithm, the control and acquisition of sensor data can continue. The process can send (**520**) the perturbation information/command to the UAV flight computer/autopilot. The process then begins (**522**) the multi-hypothesis tracking so that an optimal maneuver can be developed in the event that there are multiple detections. Using the multi-hypothesis tracking (MHT), the process can generate and propagate tracks for substantially all of the traffic detected.

While not bound by any particular theory or algorithm, the Multiple Hypothesis Tracker (MHT) is an application that provides a method for tracking in difficult conditions such as closely spaced ground targets in a cluttered background. The MHT includes deferred decision logic in which alternative data association hypotheses are formed whenever observation-to-track conflict situations occur. Then, rather than choosing the best (or most likely) hypothesis, as done in older conventional systems, the hypotheses are propagated into the future in anticipation that subsequent data will resolve the uncertainty. The MHT uses a log likelihood ratio (score) approach to assess alternative data association hypotheses. This approach readily accommodates the use of any type of metric (position, angle, etc) or feature data. Using sensor dwell information, a track score penalty can be assessed when an expected observation is not received.

After the MHT block, the process applies (**524**) an avoidance algorithm to determine an appropriate maneuver based on the information provided by the multi-hypothesis tracking. In several embodiments, the process executes one or more collision avoidance algorithms and/or tracking algorithms in determining the maneuver information. The tracking algorithms can use target dynamics and an interactive multiple model approach to maintain robust tracks. In some embodiments, for example, tracks derived from radar sensors can be combined with tracks derived from other sensors such as an ADS-B/TIS-B type sensor and optionally with additional sources of situational data such as from the UAV's electro-optical/infra-red sensors (EO/IR). In several embodiments, the process can propagate forward tracks in time to assess, detect, and prioritize potential collisions. The process can consider the kinematic capabilities of the UAV when assessing collision situations and computing avoidance maneuvers.

In one embodiment, the process executes one or more collision avoidance algorithms and/or makes computations of appropriate avoidance maneuvers using software and related technology available from Scientific Systems Company, Inc. (SCCI) of Woburn, Mass. In such case, the process can make use of SCCI's Intelligent Autonomy framework and Autonomous general navigation and control (GNC) software, which includes collision detection, dynamic path and trajectory re-planning (course, speed, and altitude) for collision avoidance in the presence of unknown threats. SCCI's unmanned vehicle control and autonomy software have been developed and tested under various Defense Advanced Research Projects Agency (DARPA) and Office of Navy Research (ONR) programs. Examples of potentially suitable algorithms include NASA's Airborne Coordinated Conflict Resolution and Detection (ACCORD), and the NASA's Autonomous Operation Planner (AOP) Tactical and Strategic Intent-Based Conflict Resolution.

After determining (**524**) the appropriate maneuver, the process then sends (**526**) the maneuver information/commands to the UAV flight control circuitry (e.g., autopilot). The process then stores (**528**) all of the collected information in a database and sorts the potential tracks. The process continues refining (**530**) the avoidance maneuver as new detection data continues to be provided to the MHT (**522**) from the radar sensors in blocks **504-516** of the process.

In one embodiment, the process can perform the sequence of actions in any order. In another embodiment, the process can skip one or more of the actions. In other embodiments, one of more of the actions are performed simultaneously. In some embodiments, additional actions can be performed.

FIG. **6** is a schematic block diagram of a collision avoidance system **600** for a UAV including various processing circuitry (**602**, **604**, **606**) in communication a variety of sensor modules (**608**, **610**, **612**, **614**) in accordance with one embodiment of the invention. The collision avoidance system **600** includes a UAV flight control unit **618** coupled to processing circuitry including avoidance processing circuitry **602**, target processing circuitry **604**, radar processing circuitry **606**, and other sensor processing circuitry **616**. The radar processing circuitry **606** is coupled to a first radar sensor **608** and a second radar sensor **610**. The other sensor processing circuitry **616** is coupled to an ADS-B sensor **612** for determining and broadcasting position of the UAV and an EO/IR sensor **614** for sensing optical and infrared information. The target processing circuitry **604** and avoidance processing circuitry **602** can process position, tracking and avoidance maneuvers based on information received from the sensor processing circuitry (**606**, **616**). In several embodiments, the collision avoidance circuitry can operate using the methods described above for FIGS. **3** and **5**.

In one embodiment, the processing circuitry controls and processes signals from the radar modules, tracks targets, and determines avoidance maneuver commands. The processing circuitry can interface with the UAV flight control computer,

the ADS-B transponder, and optionally, with other payload sensors for enhanced situational awareness. In one embodiment, the collision avoidance system can use pulsed doppler modes with pulse compression to achieve a range of 10 km with a minimum target revisit rate of 3 Hz. Monopulse processing can provide angle and range-rate accuracy to less than 2 percent and 0.9 m/sec. The collision avoidance systems are scalable for multiple platforms yielding reduced weight and power for smaller, slower platforms that do not require long range target detection. FIG. **9** is a table illustrating some of these performance parameters for a collision avoidance system for a Fire Scout UAV in accordance with one embodiment of the invention. A more detailed discussion of FIG. **9** is presented below.

In the radar sensor module shown in FIG. **6**, two radar sensors, one ADS-B and one EO/IR sensor are used. In other embodiments, more than or less than these components can be used.

FIG. **7** is a schematic block diagram of a radar sensor module **700** in accordance with one embodiment of the invention. The radar sensor module **700** includes four antennas or antenna elements **702**, a hybrid transmit/receive module **704**, a miniature digital receiver/exciter **706**, a digital processor **708**, and power supply circuitry **710**. In operation, the digital processor **708** can receive commands/instructions from a master sensor or central processing circuitry (not shown in FIG. **7**). In one case, the command is execution of a sector scan. In such case, the digital processor **708** generates the appropriate digital sector scan signals and provides them to the miniature digital receiver/exciter **706**. In some cases, the digital processor **708** performs beam steering on the generated signals. The miniature digital receiver/exciter **706** can generate radar frequency signals corresponding to the digital sector scan signals and provide them to the hybrid transmit/receive module **704**. The hybrid transmit/receive module **704** can emit the generated radar frequency signals via one or more of the antennas **702**.

As reflected radar energy is received by the antennas **702**, it is provided to the hybrid transmit/receive module **704**. The reflected radar energy is then provided to the miniature digital receiver/exciter **706** which can convert the received radar energy into digital signals and provide it to the digital processor **708**. The digital signals derived from the received radar energy can then be processed and information based thereon reported to the master sensor of the central processing circuitry.

In one embodiment, the hybrid transmit/receive module **704** is implemented using Raytheon's production Hybrid Transmit/Receive Module 4 (HTM4) and the miniature digital receiver/exciter **706** is implemented using Raytheon's production Miniature Digital Receiver/Exciter (MDREX). The digital processor can be implemented using one or more field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), or other suitable processing circuitry.

In one embodiment, a two by two array of the HTM4 modules and two MDREX form a 16 channel 160 Watts peak phased array radar. Each module can electronically scan plus or minus 45 degrees in elevation and azimuth. The MDREX can provide direct digital synthesis, up/down conversions to and from X-band, and both analog to digital and digital to analog conversion functions. The emitter elements can consist of an array of planar stripline patch antennas conforming to the HTM4 module face dimensions to provide the necessary spatial coverage. Embodiments of patch antennas are described in U.S. Pat. No. 5,325,103, the entire content of which is incorporated herein by reference. The radar sensors can be distributed around the hull of the UAV to provide full four pi steradian (sr) coverage.

Embodiments of other suitable phased array radar sensors and components for those phased array radar sensors are described in U.S. Pat. Nos. 6,965,349, 4,635,062, 5,821,901, 7,525,498, and U.S. Patent Application Number 20080030413, the entire content of each reference is incorporated herein by reference.

FIG. **8** is a perspective exploded view of a X-Band HTM4 radar transceiver in accordance with one embodiment of the invention. In several embodiments, the X-Band HTM4 radar transceiver can be used in the radar sensors described herein. In particular, the X-Band HTM4 radar transceiver can be used as the hybrid transmit/receive module of FIG. **7**.

FIG. **9** is a table illustrating performance parameters for a collision avoidance system for a Fire Scout UAV in accordance with one embodiment of the invention. In one embodiment, one or more of the collision avoidance systems described herein can be used in conjunction with a particular UAV, the Fire Scout UAV manufactured by Northrup Grumman of Century City, Los Angeles. The radar sensors can be referred to as MicroPatch (uPatch) modules/sensors. The table shown in FIG. **9** illustrates specific performance parameters for a collision avoidance system including several radar sensor/MicroPatch sensors for a Fire Scout. In other embodiments, the collision avoidance systems can be used in conjunction with other UAVs using other suitable parameters.

FIG. **10** is a graph **1000** of intruder closing speed **1002** versus range **1004** that generally illustrates baseline transmit power and track revisit rates to ensure safe UAV maneuvering rates to meet preselected safety requirements in accordance with one embodiment of the invention. For example, FIG. **10** illustrates that for a UAV traveling at 100 knots, the minimum distances required to detect an intruder/bogey and make a standard rate turn (3 percent/second) to achieve 500 feet (**1006**) and 1000 feet (**1008**) of separation is less than 5 kilometers. The margin analysis indicates that transmit power and track revisit rates are high enough to ensure safe UAV maneuvering at intruder worst case closing rates while meeting specific airspace safety requirements.

While the above description contains many specific embodiments of the invention, these should not be construed as limitations on the scope of the invention, but rather as examples of specific embodiments thereof. Accordingly, the scope of the invention should be determined not by the embodiments illustrated, but by the appended claims and their equivalents.

What is claimed is:

1. A collision avoidance system for an unmanned aerial vehicle (UAV), the system comprising:

a flight control circuitry configured to control a flight path of the UAV;

a plurality of radar sensors configured to scan for objects within a preselected range of the UAV and to store scan information indicative of the objects detected within the preselected range; and

a processing circuitry coupled to the flight control circuitry and configured to:

receive the scan information from each of the plurality of radar sensors;

determine, using multiple hypothesis tracking, maneuver information comprising whether to change the flight path of the UAV based on the scan information; and

send the maneuver information to the flight control circuitry;

wherein each of the plurality of radar sensors is configured to operate as a phased array.

2. The system of claim **1**, wherein each of the plurality of radar sensors comprises circuitry configured to generate radar signals for performing electronic scans and to electrically steer the generated radar signals.

3. The system of claim **2**, wherein the radar sensor circuitry of each of the plurality of radar sensors is configured to vary elevation and azimuth by a preselected range of degrees.

4. The system of claim **2**, wherein each of the plurality of radar sensors comprises wireless communication circuitry configured to transmit the scan information to the processing circuitry.

5. The system of claim **4**, wherein each of the plurality of radar sensors comprises:

a plurality of antenna elements;

a transceiver circuitry coupled to the plurality of antenna elements; and

a receiver/exciter circuitry coupled to the transceiver circuitry and configured to generate the radar signals and provide the radar signals to the transceiver circuitry.

6. The system of claim **5**:

wherein the receiver/exciter circuitry is configured to perform direct digital synthesis and conversions to X-band; and

wherein the transceiver circuitry is configured to electronically scan plus or minus a preselected number of degrees in elevation and azimuth.

7. The system of claim **6**, wherein each of the plurality of antenna elements comprises a planar stripline patch antenna.

8. The system of claim **1**, wherein the plurality of radar sensors are positioned at different locations along a body of the UAV.

9. The system of claim **1**, wherein the plurality of radar sensors are positioned at different locations along a body of the UAV and thereby configured to provide four pi steradian coverage.

10. The system of claim **1**, wherein the processing circuitry is configured to determine the maneuver information using a collision avoidance algorithm.

11. The system of claim **10**, wherein the processing circuitry is configured to determine the maneuver information based on kinematic capabilities of the UAV.

12. The system of claim **1**, wherein a weight of the system is less than 20 pounds.

13. The system of claim **1**, wherein each of the radar sensors is configured to operate in a pulsed doppler mode with pulse compression.

14. The system of claim **13**, wherein each of the radar sensors is configured to provide a range of approximately 10 kilometers.

15. The system of claim **1**, further comprising a wireless bus coupled to each of the plurality of radar sensors and the processing circuitry,

wherein one of the plurality of radar sensors is configured as a master radar sensor on the wireless bus and the remaining radar sensors of the plurality of radar sensors are configured as slave radar sensors on the wireless bus,

wherein the master sensor is configured to command the slave sensors to perform scans at preselected time periods.

16. The system of claim **1**, wherein the plurality of radar sensors are configured in a star-like network configuration having the processing circuitry at a logical center of the star-like network.

17. The system of claim **1**, wherein at least one of the plurality of radar sensors is positioned along a wing of the UAV.

18. The system of claim **1**, wherein each of the plurality of radar sensors are positioned at extremities of a body of the UAV, the extremities comprising a component of the UAV selected from the group consisting of a wing, a nose, and a tail.

19. The system of claim **1**, wherein the using multiple hypothesis tracking comprises generating a plurality of track hypotheses based on the scan information and propagating the track hypotheses into a future time.

20. A method for collision avoidance system for an unmanned aerial vehicle (UAV), the method comprising:

scanning for objects within a preselected range of the UAV using a plurality of phased array radar sensors;

receiving scan information from each of the plurality of phased array radar sensors, wherein the scan information comprises information indicative of objects detected within the preselected range of the UAV;

determining, using multiple hypothesis tracking, maneuver information comprising whether to change a flight path of the UAV based on the scan information; and

sending the maneuver information to a flight control circuitry of the UAV.

21. The method of claim **20**, wherein the scanning for the objects within the preselected range of the UAV using the plurality of phased array radar sensors comprises:

generating radar signals for the scanning; and

electrically steering the radar signals.

22. The method of claim **21**, wherein the electrically steering the radar signals comprises varying elevation and azimuth by a preselected range of degrees.

23. The method of claim **21**, wherein the plurality of radar sensors are positioned at different locations along a body of the UAV.

24. The method of claim **21**, wherein the plurality of radar sensors are positioned at different locations along a body of the UAV to provide four pi steradian coverage.

25. The method of claim **21**, wherein the determining the maneuver information is based on kinematic capabilities of the UAV.

26. The method of claim **21**, wherein the scanning for objects comprises operating the plurality of phased array radar sensors in a pulsed doppler mode with pulse compression.

27. The method of claim **26**, wherein each of the radar sensors is configured to provide a range of approximately 10 kilometers.

28. The method of claim **21**, wherein the determining the maneuver information comprises performing a collision avoidance algorithm.

29. The method of claim **20**, wherein the scan information is received using wireless communication circuitry.

30. The method of claim **20**, wherein each of the plurality of radar sensors comprises:

a plurality of antenna elements;

a transceiver circuitry coupled to the plurality of antenna elements; and

a receiver/exciter circuitry coupled to the transceiver circuitry and configured to generate radar signals for the scanning and to provide the radar signals to the transceiver circuitry.

31. The method of claim **30**:

wherein the receiver/exciter circuitry is configured to perform direct digital synthesis and conversions to X-band; and

wherein the transceiver circuitry is configured to electronically scan plus or minus a preselected number of degrees in elevation and azimuth.

32. The method of claim **31**, wherein each of the plurality of antenna elements comprises a planar stripline patch antenna.

33. The method of claim **20**, wherein at least one of the plurality of radar sensors is positioned along a wing of the UAV.

34. The method of claim **20**, wherein each of the plurality of radar sensors are positioned at extremities of a body of the UAV, the extremities comprising a component of the UAV selected from the group consisting of a wing, a nose, and a tail.

35. The method of claim **20**, wherein the determining, using multiple hypothesis tracking, maneuver information comprises generating a plurality of track hypotheses based on the scan information, and propagating the track hypotheses into a future time.

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