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(54) **ASSURED GEO-CONTAINMENT SYSTEM FOR UNMANNED AIRCRAFT**

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B64C 39/02	(2006.01)

(52) **U.S. Cl.**

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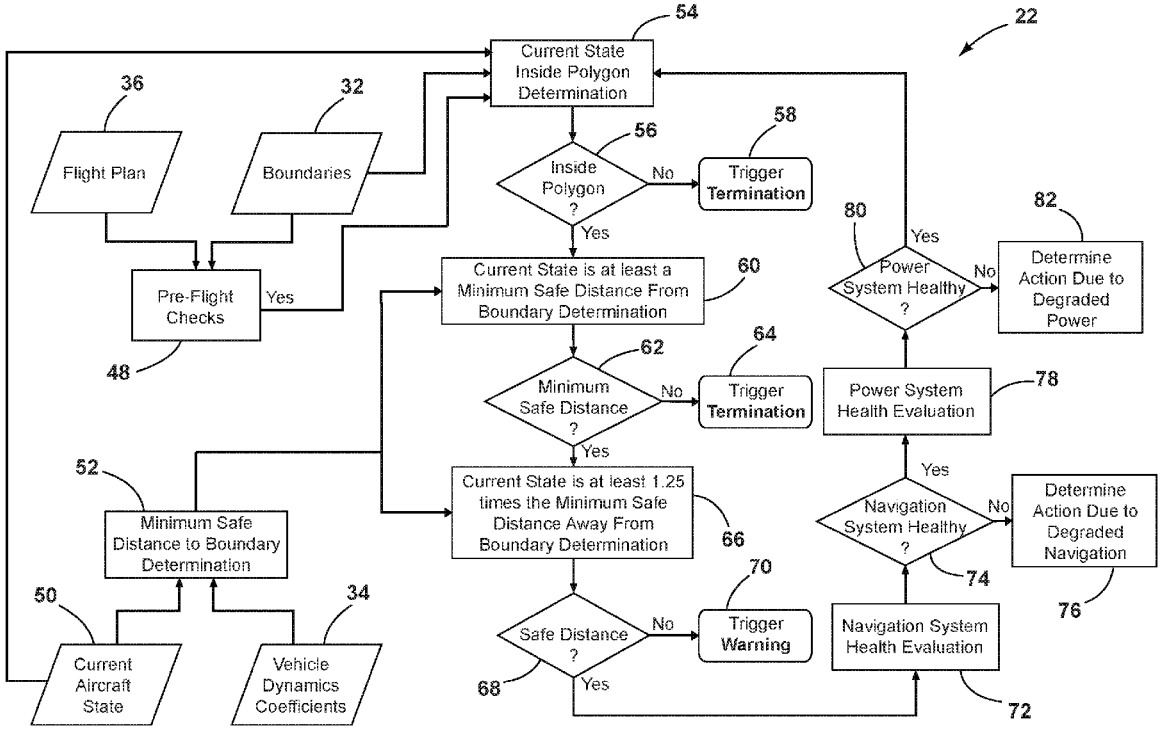
(57) **ABSTRACT**

A Geo-containment system includes at least one unmanned aircraft and a control system that is configured to limit flight of the unmanned aircraft based, at least in part, on predefined Geo-spatial operational boundaries. These boundaries may include a primary boundary and at least one secondary boundary that is spaced apart from the primary boundary a minimum safe distance. The minimum safe distance is determined while the unmanned aircraft is in flight utilizing state information of the unmanned aircraft and dynamics and dynamics coefficients of the unmanned aircraft. The state information includes at least position and velocity of the unmanned aircraft. The control system is configured to alter or terminate operation of the unmanned aircraft if the unmanned aircraft violates the primary Geo-spatial operational boundary or the secondary Geo-spatial boundary.



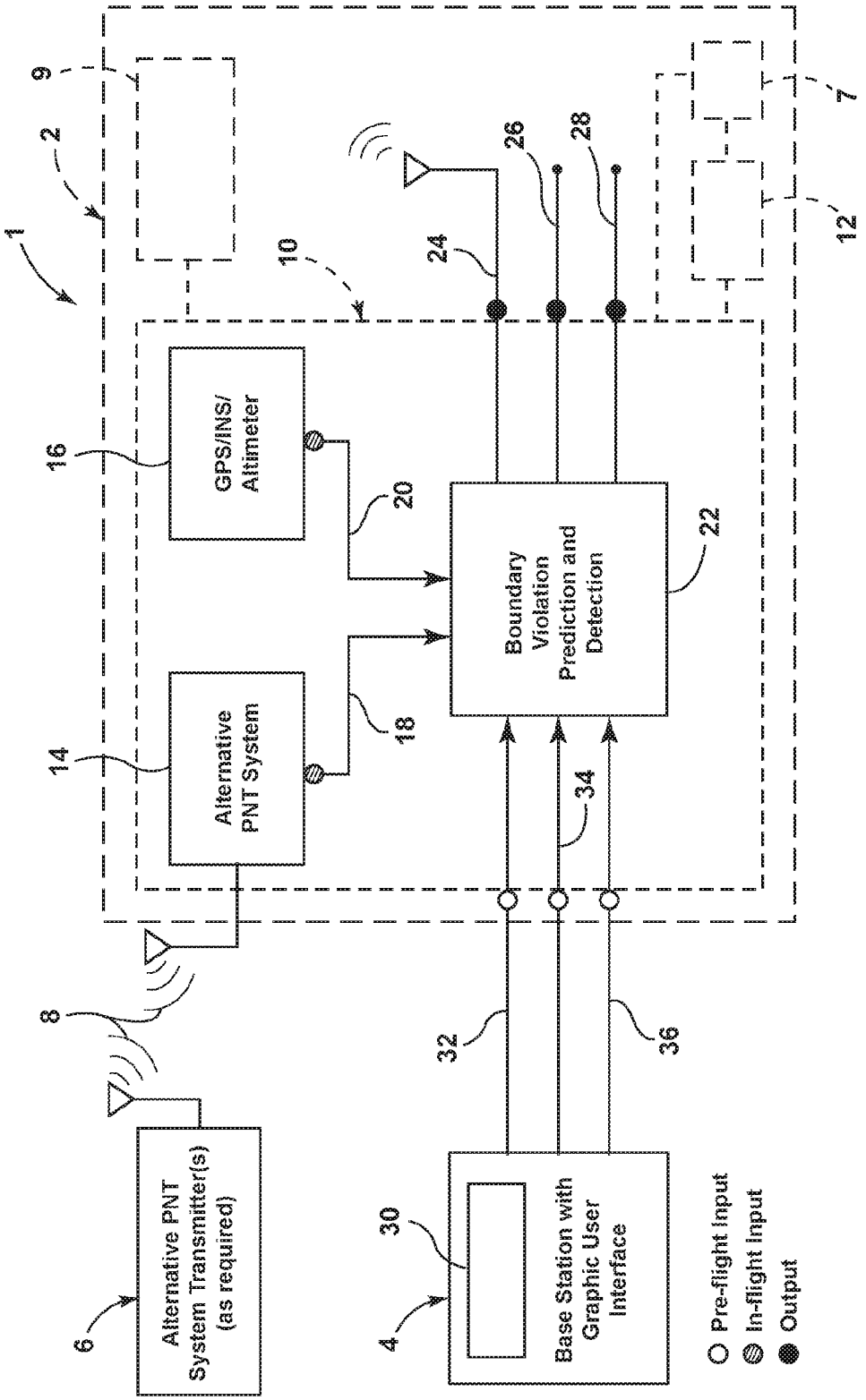

1
2
4
6
7
8
9
10
12
14
16
18
20
22
24
26
28
30
32
34
36
GPS/INS/ Altimeter
Alternative PNT System
Boundary Violation Prediction and Detection
Alternative PNT System Transmitter(s) (as required)
Base Station with Graphic User Interface
Pre-flight Input
In-flight Input
Output

FIG. 1

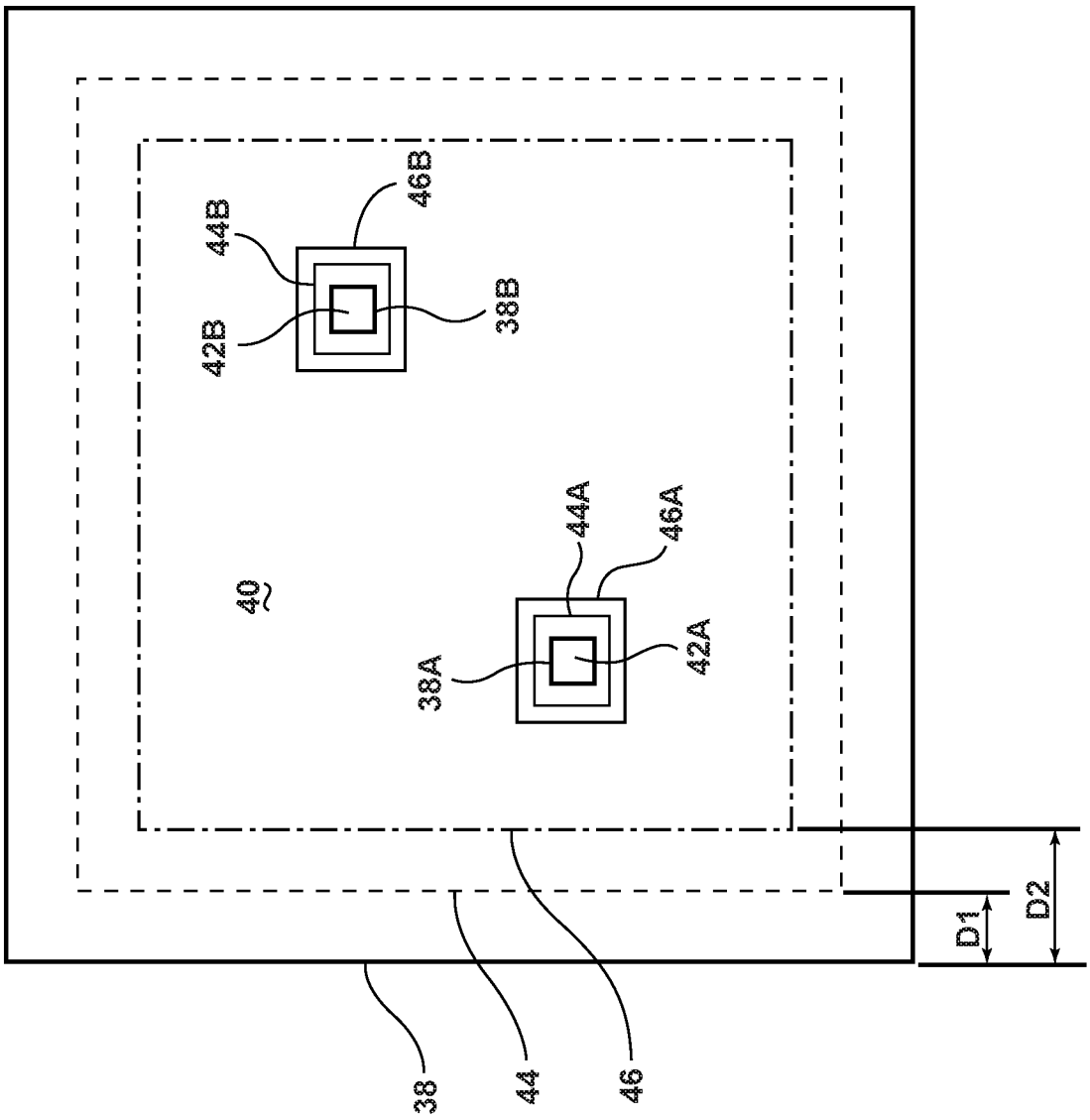


FIG. 2

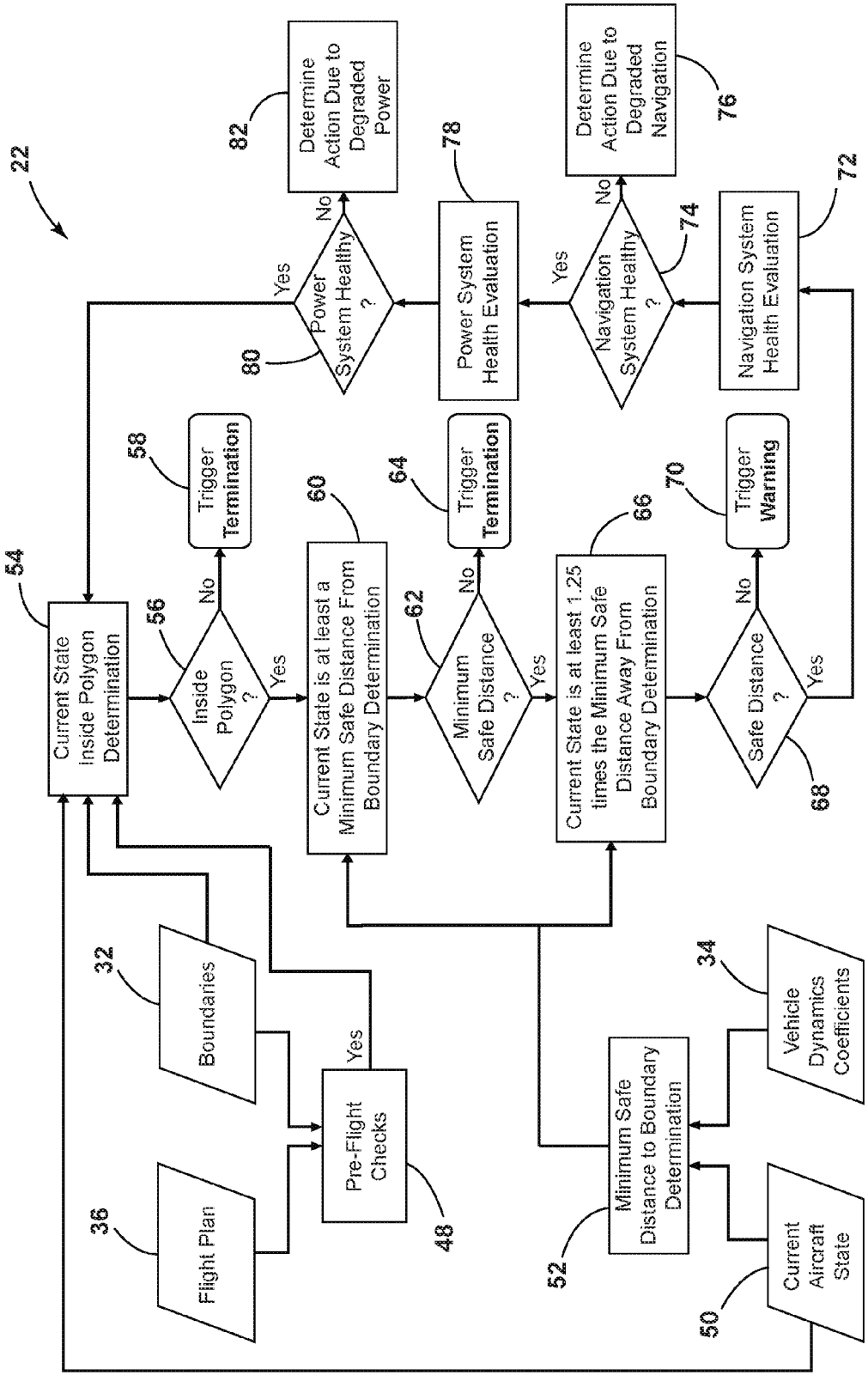

22
Current State Inside Polygon Determination
54
Inside Polygon ?
56
No
Yes
Trigger Termination
58
Current State is at least a Minimum Safe Distance From Boundary Determination
60
Minimum Safe Distance ?
62
No
Yes
Trigger Termination
64
Current State is at least 1.25 times the Minimum Safe Distance Away From Boundary Determination
66
Safe Distance ?
68
No
Yes
Trigger Warning
70
Navigation System Health Evaluation
72
Navigation System Healthy ?
74
No
Yes
Determine Action Due to Degraded Navigation
76
Power System Health Evaluation
78
Power System Healthy ?
80
No
Yes
Determine Action Due to Degraded Power
82
Boundaries
32
Flight Plan
36
Pre-Flight Checks
48
Yes
Minimum Safe Distance to Boundary Determination
52
Vehicle Dynamics Coefficients
34
Current Aircraft State
50

FIG. 3

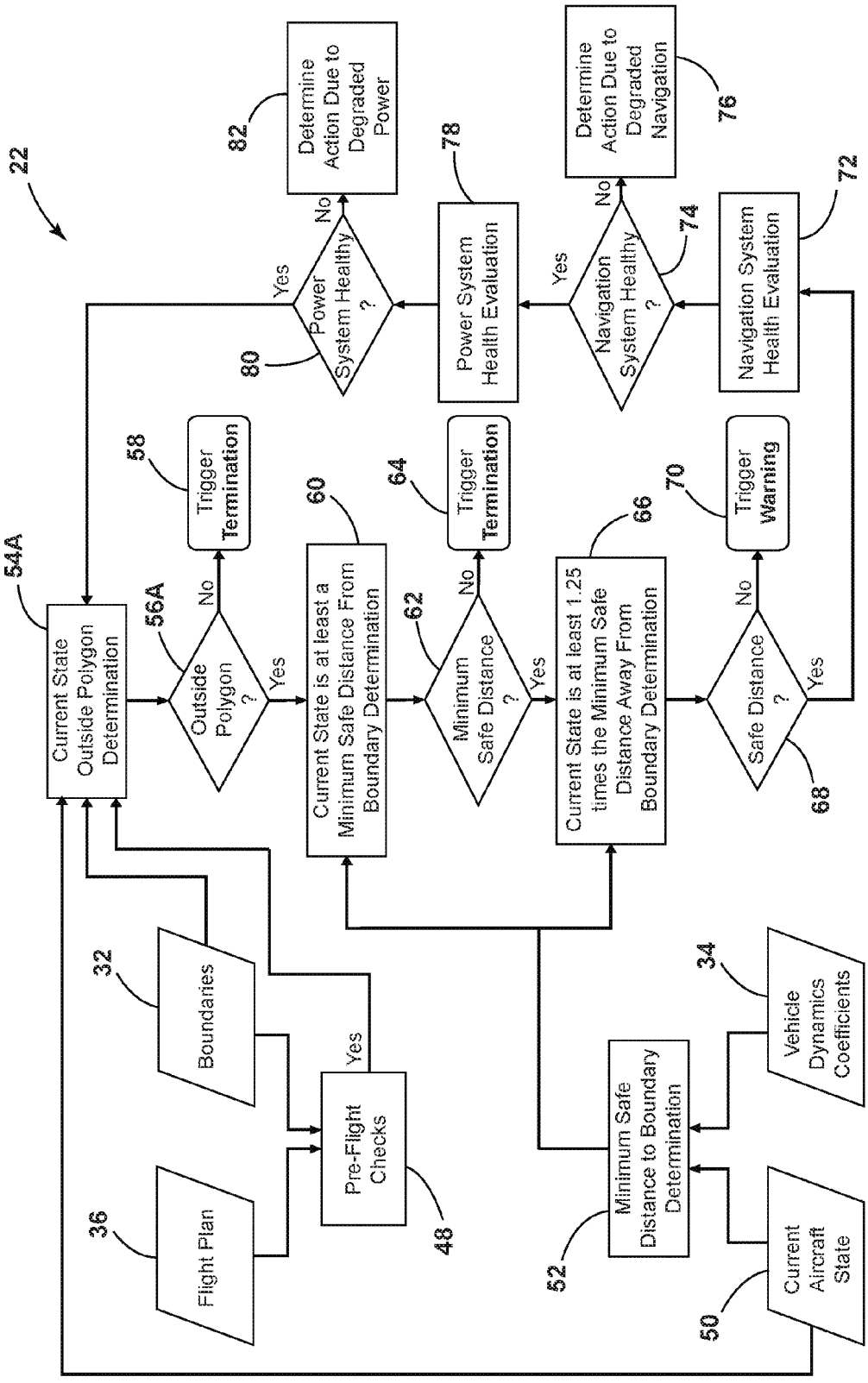

22
Current State Outside Polygon Determination
54A
Outside Polygon ?
56A
No
Trigger Termination
58
Yes
Current State is at least a Minimum Safe Distance From Boundary Determination
60
Minimum Safe Distance ?
62
No
Trigger Termination
64
Yes
Current State is at least 1.25 times the Minimum Safe Distance Away From Boundary Determination
66
Safe Distance ?
68
No
Trigger Warning
70
Yes
Navigation System Health Evaluation
72
Navigation System Healthy ?
74
No
Determine Action Due to Degraded Navigation
76
Yes
Power System Health Evaluation
78
Power System Healthy ?
80
No
Determine Action Due to Degraded Power
82
Yes
Boundaries
32
Flight Plan
36
Pre-Flight Checks
48
Yes
Minimum Safe Distance to Boundary Determination
52
Vehicle Dynamics Coefficients
34
Current Aircraft State
50

FIG. 4

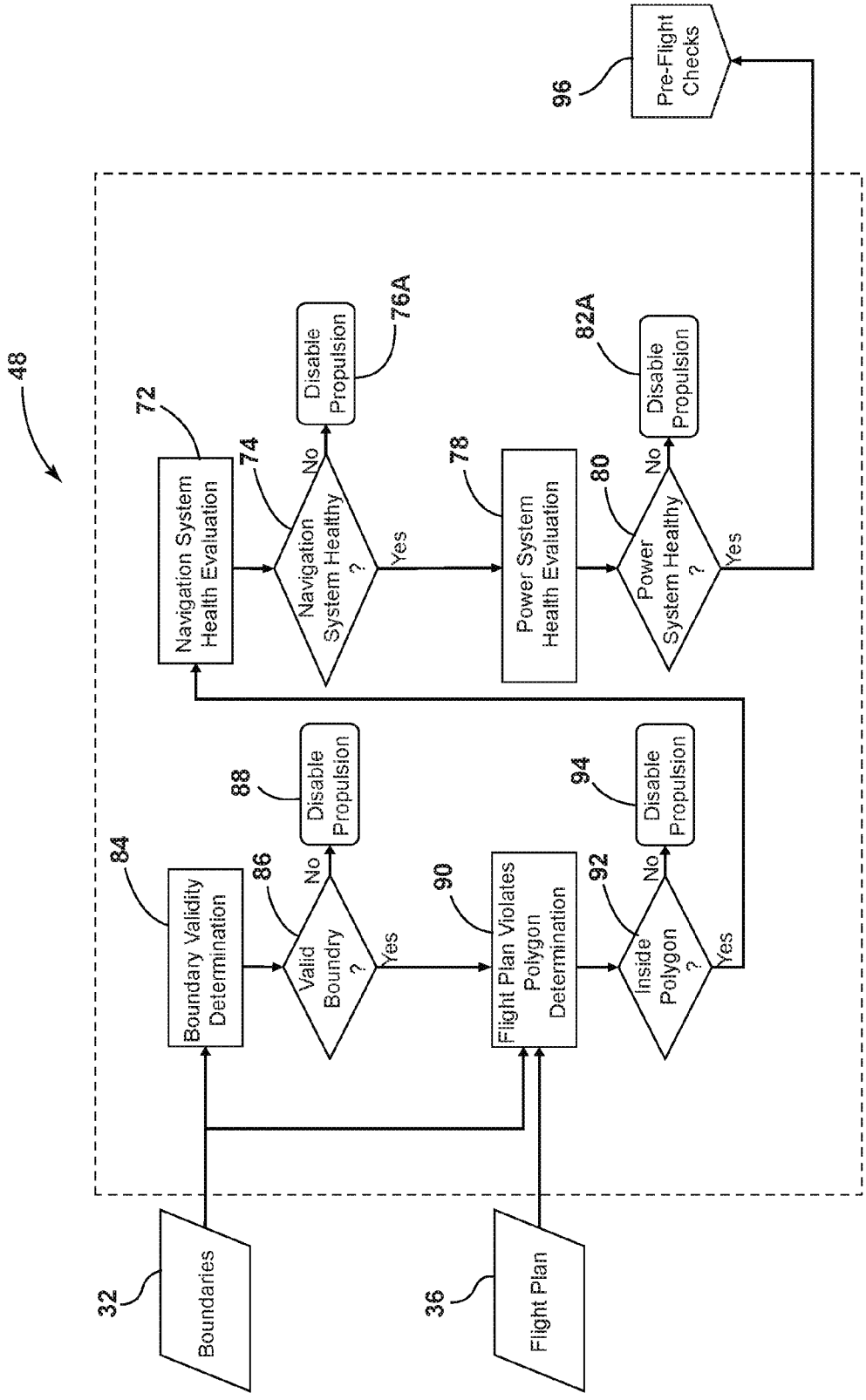

48
32
Boundaries
36
Flight Plan
84
Boundary Validity Determination
86
Valid Boundry ?
No
Yes
88
Disable Propulsion
90
Flight Plan Violates Polygon Determination
92
Inside Polygon ?
No
Yes
94
Disable Propulsion
72
Navigation System Health Evaluation
74
Navigation System Healthy ?
No
Yes
76A
Disable Propulsion
78
Power System Health Evaluation
80
Power System Healthy ?
No
Yes
82A
Disable Propulsion
96
Pre-Flight Checks

FIG. 4A

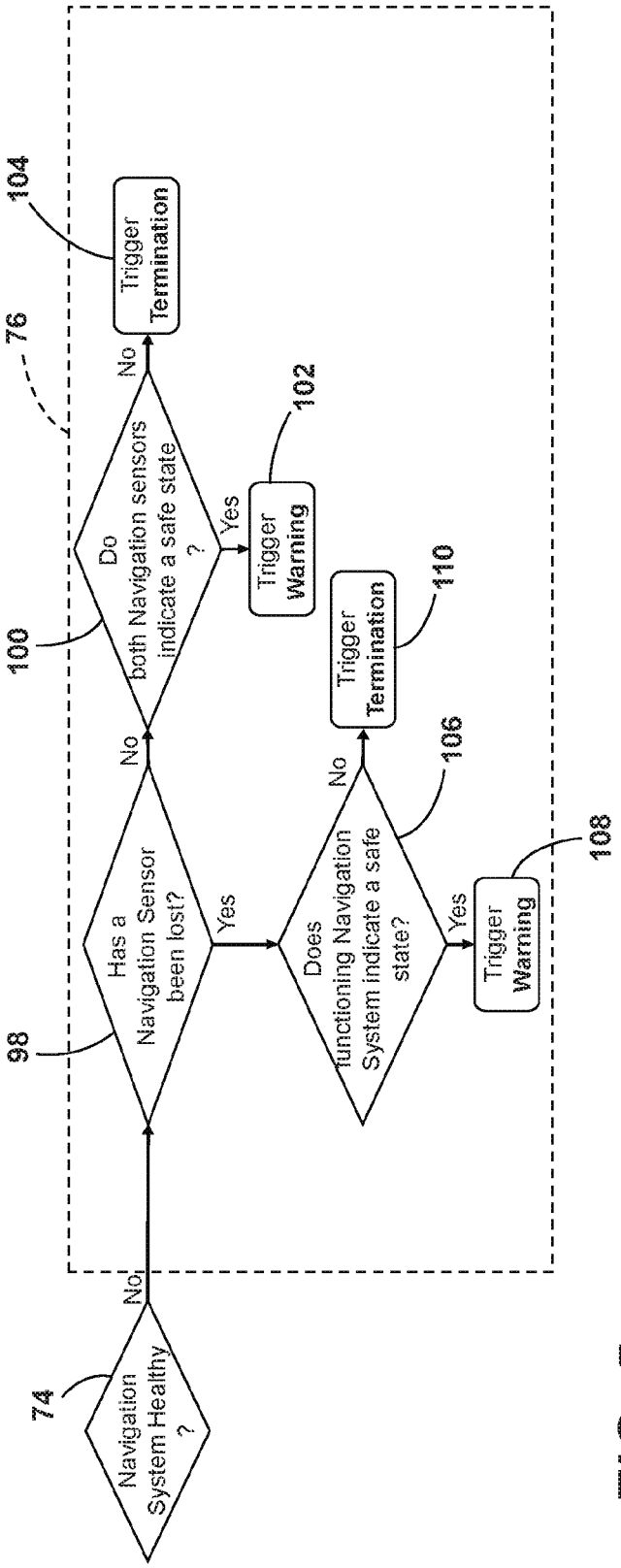

74
Navigation System Healthy ?
No
98
Has a Navigation Sensor been lost?
Yes
No
106
Does functioning Navigation System indicate a safe state?
Yes
108
Trigger Warning
No
110
Trigger Termination
100
Do both Navigation sensors indicate a safe state ?
Yes
102
Trigger Warning
No
76
104
Trigger Termination

FIG. 5

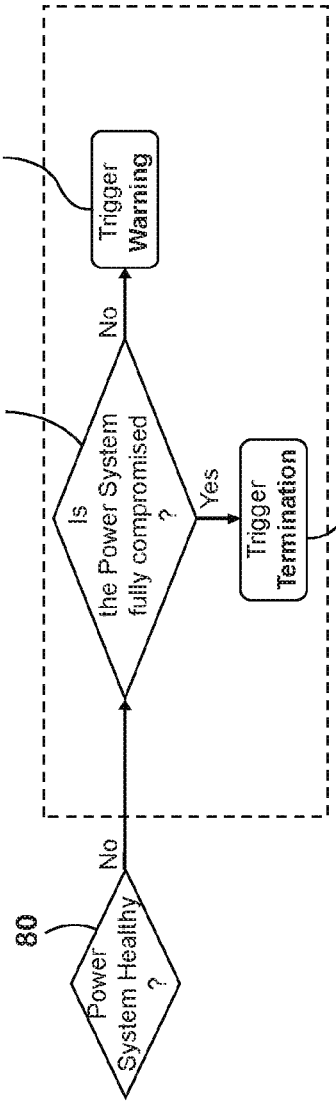

80
Power System Healthy ?
No
112
Is the Power System fully compromised ?
Yes
112
Trigger Termination
No
114
Trigger Warning

FIG. 6

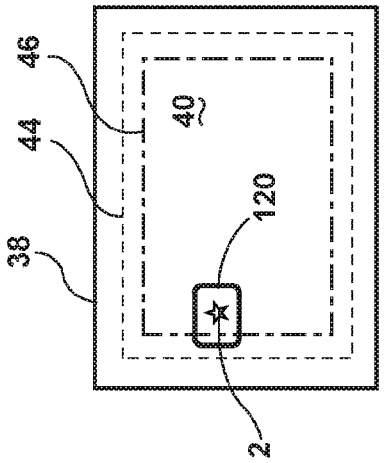


FIG. 7A

FIG. 7B

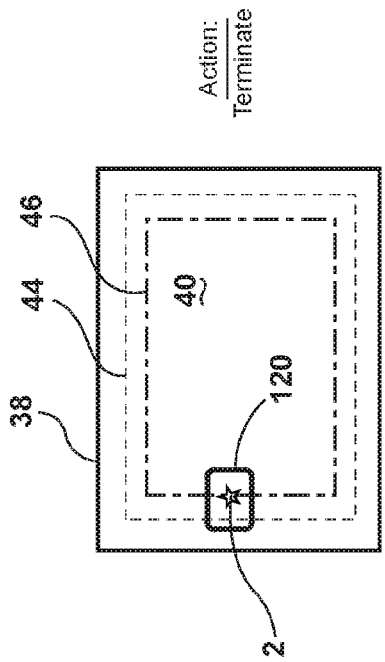


FIG. 7C

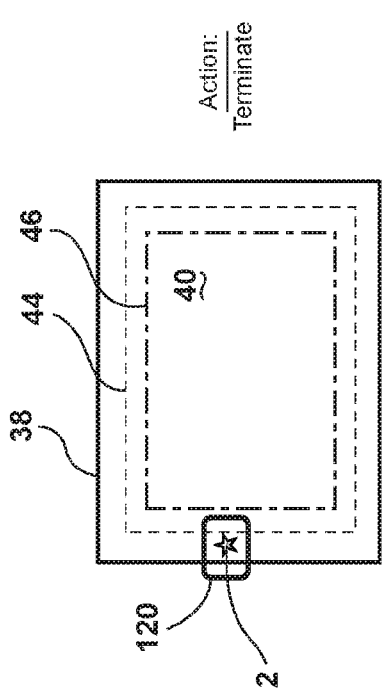


FIG. 7D

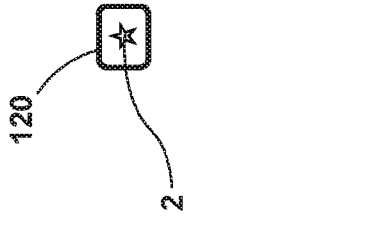


FIG. 8A

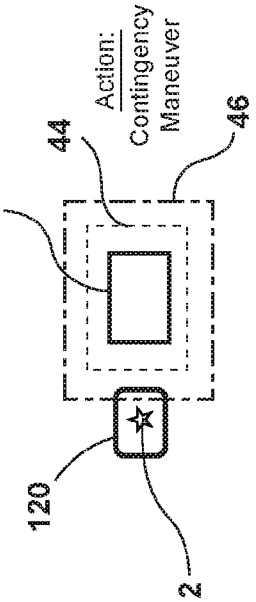


FIG. 8B

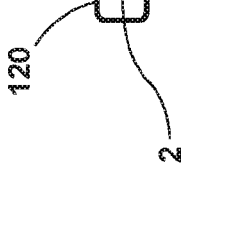


FIG. 8C

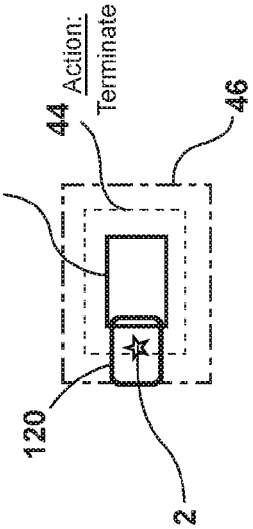


FIG. 8D

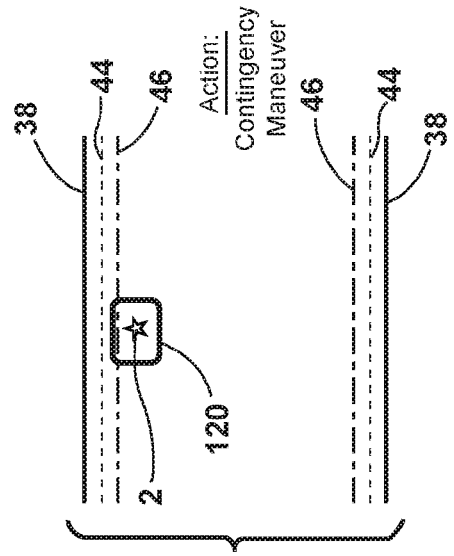


FIG. 9B

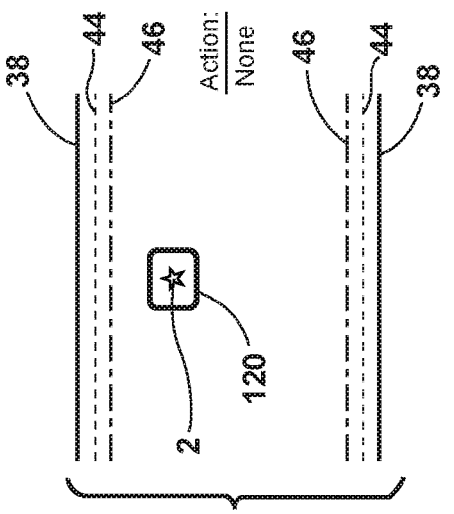


FIG. 9A

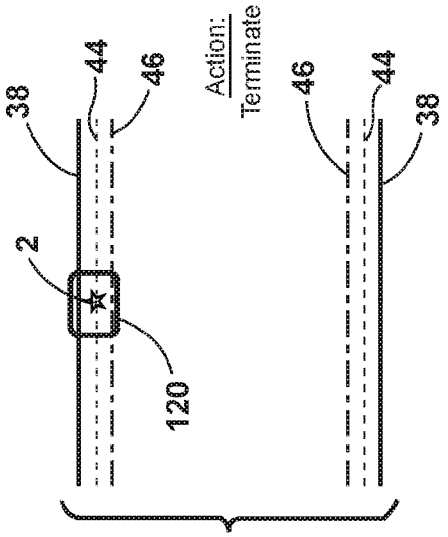


FIG. 9D

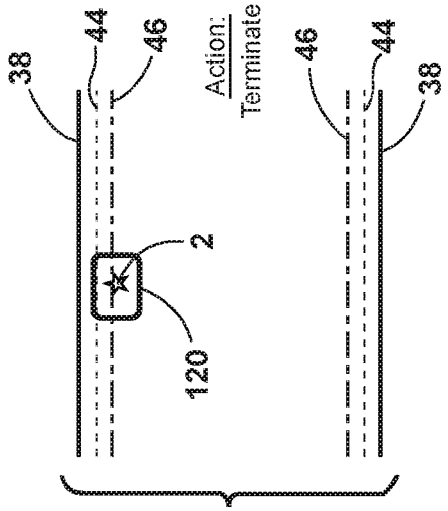


FIG. 9C

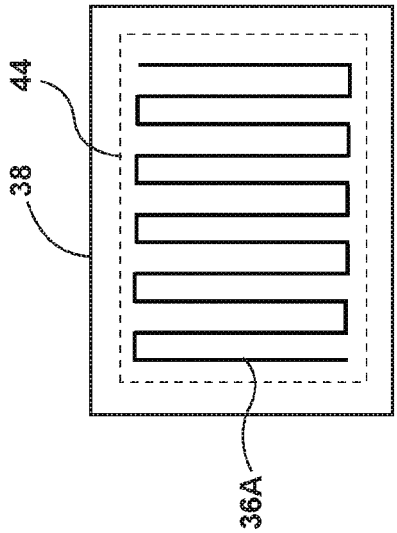


FIG. 10A

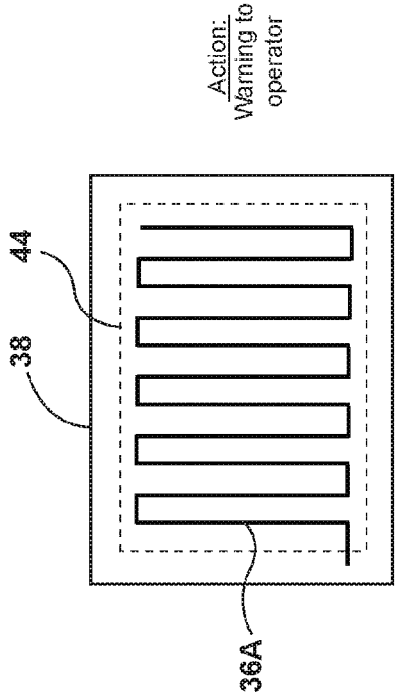


FIG. 10B

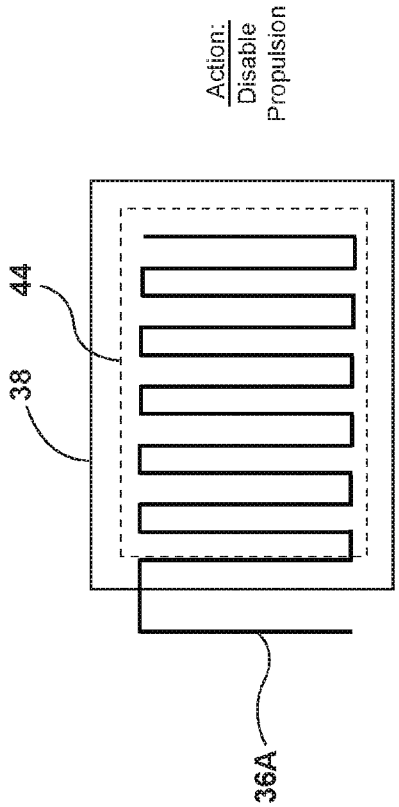


FIG. 10C

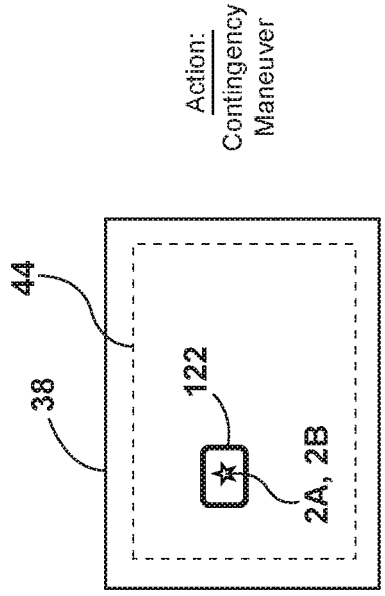


FIG. 11A

FIG. 11B

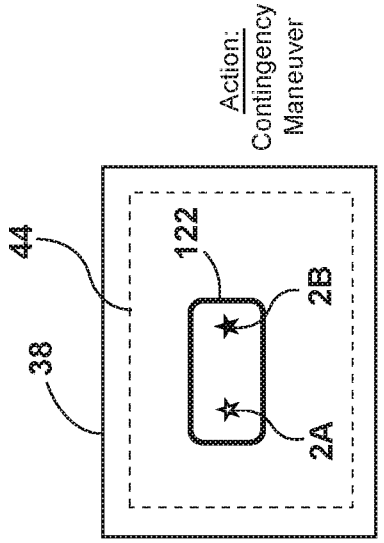


FIG. 11C

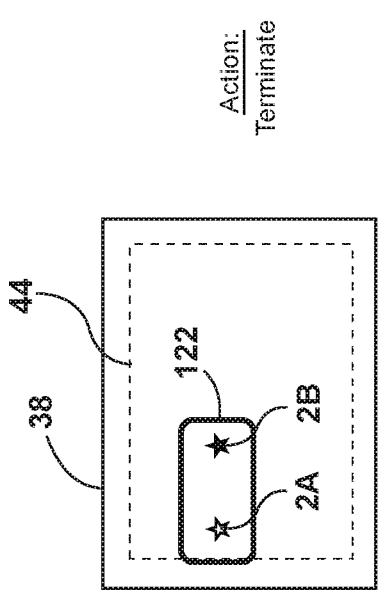


FIG. 11D

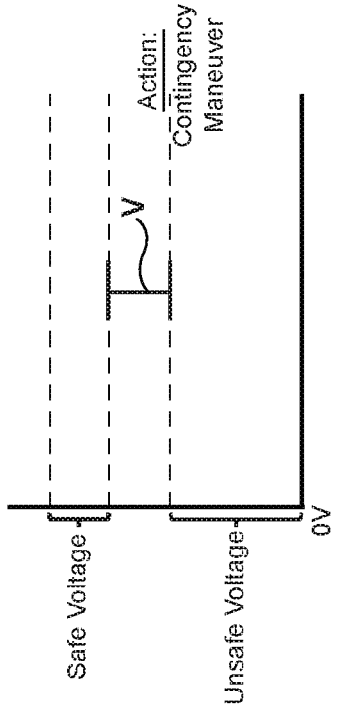


FIG. 12A

FIG. 12B

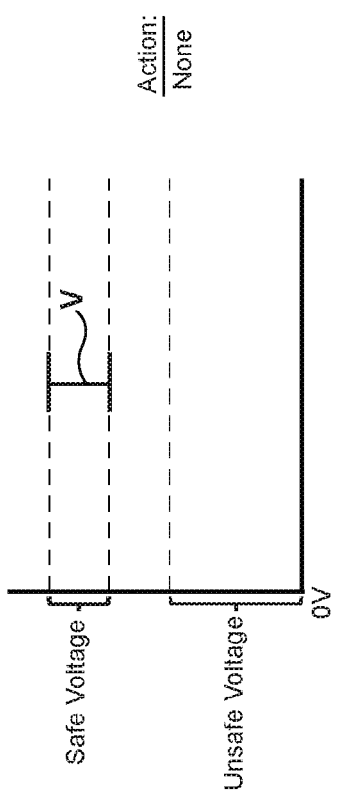


FIG. 12C

FIG. 12D

ASSURED GEO-CONTAINMENT SYSTEM FOR UNMANNED AIRCRAFT

CROSS-REFERENCE TO RELATED PATENT APPLICATION(S)

[0001] This patent application claims the benefit of and priority to U.S. Provisional Patent Application No. 62/272,742, filed on Dec. 30, 2015, and U.S. Provisional Patent Application No. 62/329,234, filed on Apr. 29, 2016, the contents of which are hereby incorporated by reference in their entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] The invention described herein was made in the performance of work under a NASA contract and by employees of the United States Government and is subject to the provisions of the National Aeronautics and Space Act, Public Law 111-314, §3 (124 Stat. 3330, 51 U.S.C. Chapter 201), and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

[0003] Various types of unmanned aircraft systems (UAS) have been developed. UAS typically include ground-based controllers that communicate wirelessly with unmanned aircraft (UA). The Federal Aviation Administration (FAA) has received numerous reports from pilots, aircraft controllers and others about unmanned aircraft operating in areas that can put people on the ground and/or other aircraft in direct harm (i.e., operating where they should not be). Examples include unplanned UA operations near other aviation activities, near firefighting activities, and operation over populated, private or secured areas.

[0004] Legislation has been proposed to mandate technology, such as geo-fencing, to prevent such events. Geo-fencing systems are available today for some UA that provide some functionality to prevent unmanned aircraft from entering "no-fly" zones. However, existing geo-fencing technology may rely on GPS and/or non-aviation-grade autopilot systems that are subject to failure. Thus, existing geo-fencing technology does not meet current civil aviation-grade standards for reliability and integrity.

BRIEF SUMMARY OF THE INVENTION

[0005] The present disclosure includes a system for unmanned aircraft to automatically detect established boundaries of a designated geospatial operational area and prevent the unmanned aircraft (UA) from crossing the boundaries. In general, the system operates by using real-time data about the position of a UA to determine the proximity of a UA to pre-defined operational boundaries (horizontal and vertical), using a system of buffers defined for each boundary. The operational boundaries may be provided (at least in part) in databases with established "no-fly" zones (much like existing aeronautical maps). The boundaries may also be provided (uploaded) by the UAS operator. If the positioning data indicates that the UA has crossed into a buffer, the system sends a signal to the autopilot to make an optional, pre-determined contingency maneuver to avoid crossing the boundary. If the contingency maneuver fails and the aircraft continues through the buffer, the system automatically activates a flight termination maneuver prior to breaching the operational boundary. The system may use real-time positioning (that is not solely reliant on the UAS autopilot or GPS), in the scheme that is used to detect impending boundary violations. These features may be included in a system architecture that facilitates certification. A system according to the present disclosure may be utilized to provide an assured safety net for practically all unmanned aircraft operations.

[0006] An assured geo-containment system according to the present disclosure provides numerous benefits. Specifically, the system may be independent of the UA and any on-board components, such as the autopilot. Also, the positioning system does not need to rely solely on GPS. Rather, a fully GPS-independent positioning source may be used to obtain geo-referenced state data. Furthermore, the boundaries for the no-fly-zones may be described with virtually any polygon. Thus, there are practically no limits on the shape or number of boundaries. Still further, the algorithms (criteria) for establishing whether a boundary is valid and for detecting proximity to all defined boundaries are based on rigorous mathematical models that have been formally verified.

[0007] One aspect of the present disclosure is a Geo-containment system including at least one unmanned aircraft. The Geo-containment system operates in conjunction with a termination system that is configured to limit flight of the unmanned aircraft based, at least in part, on predefined geo-spatial operational boundaries. The geo-spatial operational boundary may optionally include a stay-in region and/or one or more stay-out regions. The predefined geo-spatial operational boundaries include a primary geo-spatial operational boundary and at least one secondary geo-spatial operational boundary that is spaced apart by a minimum safe distance from the primary geo-spatial operational boundary. The minimum safe distance is determined while the unmanned aircraft is in flight utilizing, at least in part: 1) state information of the unmanned aircraft including at least altitude and velocity of the unmanned aircraft, and 2) dynamics coefficients of the unmanned aircraft. The system is configured to alter or terminate operation of the unmanned aircraft if the unmanned aircraft violates either the primary geo-spatial operational boundary or the secondary geo-spatial boundary. A violation may occur if the unmanned aircraft moves to a position in which the unmanned aircraft is less than a minimum allowable distance from either the primary geo-spatial boundary or the secondary geo-spatial boundary. The minimum allowable distance may also include an uncertainty term (i.e. potential error) with respect to a location of the unmanned aircraft.

[0008] The at least one secondary geo-spatial boundary may include a warning boundary and a soft boundary, wherein the soft boundary is located between the warning boundary and the primary geo-spatial boundary. The soft boundary may be at the minimum safe distance from the primary geo-spatial boundary, and the warning boundary may be spaced apart from the primary geo-spatial operational boundary a distance that is a scale factor, p multiplied by the minimum safe distance. The scale factor may be 1.25 or other suitable value. The control system may be configured to generate a warning if the unmanned aircraft crosses the warning boundary. The unmanned aircraft may include an auto-pilot system or other suitable control feature that causes the unmanned aircraft to perform a contingency maneuver (e.g. land the unmanned aircraft) if a warning

signal is generated by the control system. The contingency maneuver may include at least one of, but is not limited to, causing the unmanned aircraft to turn, reduce altitude, and/or reduce speed.

[0009] The Geo-containment system (i.e. the unmanned aircraft) may include a first navigation system that is GPS-based, and a second navigation system that is GPS-independent. The first navigation system may provide a position of the unmanned aircraft during flight within a first error distance, and the second navigation system may provide a position of the unmanned aircraft during flight within a second error distance. The allowable distance may comprise the greater of the first and second error distances. The second navigation system may comprise virtually any suitable alternative positioning system. The system may be configured to evaluate a flight plan prior to flight of the unmanned aircraft to determine if the flight plan will cause the unmanned aircraft to violate the primary geo-spatial operational boundary and/or the secondary geo-spatial boundary.

[0010] These and other features, advantages, and objects of the present invention will be further understood and appreciated by those skilled in the art by reference to the following specification, claims, and appended drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0011] FIG. **1** is a schematic representation of a geo-containment system for unmanned aircraft according to one aspect of the present disclosure;

[0012] FIG. **2** is a schematic plan view showing boundaries of stay-in regions and stay-out regions that may be used by the system;

[0013] FIG. **3** is a diagram showing detection logic for stay-in regions;

[0014] FIG. **4** is a diagram showing detection logic for stay-out regions;

[0015] FIG. **4**A is a diagram showing boundary violation prediction and detection logic for preflight checks;

[0016] FIG. **5** is a diagram showing operating logic for navigation system monitoring;

[0017] FIG. **6** is a diagram showing operating logic for system power monitoring;

[0018] FIG. **7**A is a schematic plan view showing lateral boundary evaluation logic for stay-in regions in which an error ellipse is defined around an unmanned aircraft that is inside all boundaries;

[0019] FIG. **7**B is a schematic plan view showing lateral boundary evaluation logic for stay-in regions in which the error ellipse has breached a warning boundary;

[0020] FIG. **7**C is a schematic plan view showing lateral boundary evaluation logic for stay-in regions in which the error ellipse has breached a soft boundary;

[0021] FIG. **7**D is a schematic plan view showing lateral boundary evaluation logic for stay-in regions in which the error ellipse has breached a hard boundary;

[0022] FIG. **8**A is a schematic plan view showing lateral boundary evaluation logic for stay-out regions in which an error ellipse defined around an unmanned aircraft is outside all boundaries;

[0023] FIG. **8**B is a schematic plan view showing lateral boundary evaluation logic for stay-out regions in which the error ellipse has breached a warning boundary;

[0024] FIG. **8**C is a schematic plan view showing lateral boundary evaluation logic for stay-out regions in which the error ellipse has breached a soft boundary;

[0025] FIG. **8**D is a schematic plan view showing lateral boundary evaluation logic for stay-out regions in which the error ellipse has breached a hard boundary;

[0026] FIG. **9**A is a schematic view showing vertical boundary evaluation logic in which an error ellipse around a position of an unmanned aircraft is inside of all boundaries;

[0027] FIG. **9**B is a schematic view showing vertical boundary evaluation logic in which the error ellipse has breached a warning boundary;

[0028] FIG. **9**C is a schematic view showing vertical boundary evaluation logic in which the error ellipse has breached a soft boundary;

[0029] FIG. **9**D is a schematic view showing vertical boundary evaluation logic in which the error ellipse has breached a hard boundary;

[0030] FIG. **10**A is a schematic plan view showing preflight flight plan evaluation logic for normal operation;

[0031] FIG. **10**B is a schematic plan view showing preflight flight plan evaluation logic with flight plan warning;

[0032] FIG. **10**C is a schematic plan view showing preflight flight plan evaluation logic in which the flight plan is invalid;

[0033] FIG. **11**A is a schematic plan view showing navigation system evaluation logic for normal operation;

[0034] FIG. **11**B is a schematic plan view showing navigation system evaluation logic in which there is a loss of one navigation system;

[0035] FIG. **11**C is a schematic plan view showing navigation system evaluation logic in which an unacceptable but safe position discrepancy is detected;

[0036] FIG. **11**D is a schematic plan view showing navigation system evaluation logic in which an unacceptable and unsafe position discrepancy is detected;

[0037] FIG. **12**A is a graph showing power system evaluation logic for normal operation;

[0038] FIG. **12**B is a graph showing power system evaluation logic for a low voltage condition;

[0039] FIG. **12**C is a graph showing power system evaluation logic for a dangerously low or zero voltage condition; and

[0040] FIG. **12**D is a graph showing power system evaluation logic for an excessively high voltage condition.

DETAILED DESCRIPTION OF THE INVENTION

[0041] For purposes of description herein, the terms "upper," "lower," "right," "left," "rear," "front," "vertical," "horizontal," and derivatives thereof shall relate to the invention as oriented in FIG. **1**. However, it is to be understood that the invention may assume various alternative orientations and step sequences, except where expressly specified to the contrary. It is also to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification, are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting, unless the claims expressly state otherwise.

[0042] With reference to FIG. **1**, an assured Geo-containment system **1** for unmanned aircraft according to one aspect of the present disclosure includes an unmanned aircraft **2** that may be operably connected to a base station **4**. It will be understood that the term "aircraft" as used herein is not limited to any specific type of aircraft, but rather refers to virtually any type of flying device such as a helicopter, drone, winged aircraft, rocket, etc. Unmanned aircraft **2** may include a controller **10** that is operably connected to a propulsion system **12**. It will be understood that the controller **10** may have virtually any suitable configuration, and may include a programmable controller, electrical circuit components, software, and/or other components. Unmanned aircraft **2** may be configured to wirelessly interact with an alternate positioning, navigation, and timing ("PNT") system **6**. The system **1** further includes a GPS system **16**. The PNT system **14** provides GPS-independent data **18** to a boundary violation prediction and detection component **22**, and GPS system **16** provides GPS-based position data **20** to the boundary violation prediction and detection component **22**. The boundary violation prediction and detection component **22** may comprise a programmable controller, executable software or other suitable arrangement. As discussed in more detail below, the boundary violation prediction and detection component **22** may provide an output **24** comprising diagnostic output or a message, a termination output **26**, or a warning output **28**.

[0043] Referring again to FIG. **1**, the base station **4** may include a graphical user interface **30** or other suitable device/feature that provides graphical and/or text data to a user, and also permits a user to input boundary points **32**, vehicle dynamics coefficients **34**, and flight plan data **36**. These pre-flight inputs are evaluated by the boundary violation prediction and detection component **22** before and during flight of unmanned aircraft **2**.

[0044] Unmanned aircraft **2** also includes an auto pilot that is operably connected to boundary violation prediction and detection component **22** and a propulsion system **12** that is operably connected to boundary violation prediction and detection component **22** and/or propulsion system **12**. Unmanned aircraft **2** may also include an electrical power source/system **9** that provides electrical power to the various onboard electrical components.

[0045] With reference to FIG. **2**, the boundary points **32** define one or more hard boundaries **38**, **38**A, **38**B, etc. In the illustrated example, the hard boundary **38** forms a stay-in region **40**. The hard boundary **38**A forms a stay-out region **42**A, and the hard boundary **38**B forms a stay-out region **42**B. FIG. **2** is a schematic plan view of a geographical area, and the hard boundaries **38**, **38**A, **38**B represent lateral boundaries. As discussed in more detail below, the system **1** may also utilize one or more vertical boundaries to limit the vertical position of the unmanned aircraft **2**. The boundary violation prediction and detection component **22** of system **1** is configured to determine a soft boundary **44** and a warning boundary **46**. The soft boundary **44** is spaced apart from hard boundary **38** a distance "D**1**," and the warning boundary **46** is spaced apart from the hard boundary **38** a distance "D**2**." As discussed in more detail below, the distance D**1** may be equal to a minimum safe distance that is determined by the boundary violation prediction and detection component **22** utilizing vehicle dynamics coefficients **34** (FIG. **1**) and position and velocity of unmanned aircraft **2** as determined by PNT system **14** and/or GPS system **16**. In general, the distance D**2** is greater than the distance D**1**. For example, the distance D**2** may be 1.25 times the distance D**1**. However, other multiples (e.g. 1.2, 1.3, 1.5, 2.0, etc.) or criteria may also be utilized to calculate distance D**2**. The boundary violation prediction and detection component **22** of system **1** may also determine soft boundaries **44**A and **44**B, and warning boundaries **46**A and **46**B for stay-out regions **42**A and **42**B. Although the hard boundaries **38**, **38**A, **38**B, etc. are determined prior to flight of unmanned aircraft **2** utilizing boundary point data **32**, the locations of the soft boundary **44** and warning boundary **46** corresponding to distances D**1** and D**2**, respectively, are calculated in-flight by the boundary violation prediction and detection component **22**. The distances D**1** and D**2** may be calculated and updated at a high frequency (e.g. 100 or 1000 times or more per second).

[0046] Boundary violation prediction and detection logic for stay-in regions (e.g. stay-in region **40** of FIG. **2**) during operation of the Geo-containment system **1** is shown in FIG. **3**. Similarly, the boundary violation prediction and detection logic for stay-out regions is shown in FIG. **4**. The operating logic of FIGS. **3** and **4** is preferably implemented utilizing boundary violation prediction and detection component **22**. It will be understood that the logic diagrams of FIGS. **3** and **4** are not necessarily limited to specific sequences or steps.

[0047] Referring to FIG. **3**, flight plan data **36** and boundary data **32** are input into pre-flight checks **48**. As discussed in more detail below, the pre-flight checks **48** may include evaluating the flight plan **36** to determine if the flight plan will violate a boundary. The vehicle dynamics coefficients **34** and current aircraft state **50** are utilized in a minimum safe distance to boundary determination **52**. The minimum safe distance to boundary is shown schematically as the distance D**1** in FIG. **2**. The block **54** represents a determination if the unmanned aircraft **2** is presently inside a polygon (e.g. hard boundary **38**). As shown at **56** and **58**, if the unmanned aircraft **2** is not inside the polygon (hard boundary **38**), the system triggers termination as shown at **58**. Termination may constitute shutting down the propulsion system **12** or other action to immediately stop the flight of the unmanned aircraft **2**. Although termination preferably involves eliminating all thrust from propulsion system **12**, termination may also comprise reducing propulsion and/or maneuvering the unmanned aircraft **2** so it lands immediately with minimal additional travel.

[0048] If the unmanned aircraft **2** is determined to be inside the polygon/hard boundary **38** at step **56**, the system then determines if the current state is at least a minimum safe distance D**1** from a hard boundary at steps **60** and **62**. It will be understood that this is equivalent to determining if the aircraft has crossed ("violated") the soft boundary **44** (FIG. **2**). If the unmanned aircraft **2** is at a distance that is less than the minimum safe distance, the system triggers termination as shown at **64**. As discussed above, termination may include reducing or eliminating the thrust of propulsion system **12**.

[0049] As shown at **66** and **68**, the system also determines if the current state is at least 1.25 times the minimum safe distance away from the boundary determination. It will be understood that this is equivalent to determining if the unmanned aircraft **2** has crossed ("violated") the warning boundary **46** (FIG. **2**). If the unmanned aircraft **2** has crossed the warning boundary **46**, the system triggers a warning as shown at **70**. Warning **70** may comprise an audio or visual

warning to a user (e.g. utilizing graphical user interface **30** and/or speakers of base station **4** (FIG. **1**)). The warning **70** may also include or trigger a flight maneuver by an auto pilot system of unmanned aircraft **2**. The flight maneuver may be a maneuver that, if possible, changes a flight path of the unmanned aircraft **2** to avoid crossing soft boundary **44**, and also avoids hard boundary **38**. If the flight maneuver fails to avoid crossing the soft boundary **44**, termination is triggered as shown at step **64**.

[0050] As shown at steps **72**, **74**, and **76**, if the unmanned aircraft **2** is at a safe distance (step **68**), the system evaluates the health of the navigation system at **72**, and determines an action at step **76** if the navigation system has been degraded. The navigation system health evaluation is discussed in more detail below in connection with FIG. **5**.

[0051] As shown at **78**, **80**, and **82**, the system also evaluates/monitors the health of the power system **9** of the aircraft and takes action at step **82** if the power system **9** has degraded. The power system monitoring is discussed in more detail below in connection with FIG. **6**.

[0052] The operating logic of FIG. **4** for stay-out regions is substantially similar to the operating logic for stay-in regions (FIG. **3**) discussed above. However, at steps **54**A and **56**A, the system determines if the aircraft is outside of the polygon, rather than determining if the system is inside the polygon as shown at steps **54** and **56** of FIG. **3**. It will be understood that the operating logic of FIGS. **3** and **4** may be utilized simultaneously to control unmanned aircraft **2** if the unmanned aircraft **2** is operating in a region that includes both stay-in regions and stay-out regions as shown in FIG. **2**.

[0053] With further reference to FIG. **4**A, the pre-flight check **48** utilizes the boundary inputs **32** to determine if a valid boundary has been entered as shown at **84** and **86**. If the boundary is not valid (e.g. edges of the boundary cross each other and/or have very sharp corners), propulsion is disabled as shown at **88**. One or more of the following criteria may be utilized to determine if a boundary (polygon) is valid:

[0054] (1) The vertices of the polygon region must be in counter-clockwise order;

[0055] (2) No two non-adjacent boundary edges of the polygon region can cross each other or be closer than a first predefined minimum distance;

[0056] (3) For two adjacent boundary edges, neither of their non-shared endpoints can be less than a second predefined minimum distance from the other edge;

[0057] (4) Two adjacent boundary edges of the polygon region cannot form a sharp corner, (e.g. less than 3 degrees); and

[0058] (5) No boundary edge can be less than a predefined minimum length (e.g. 1.0 meter or 0.1 meter).

[0059] As shown at steps **90** and **92**, the boundary data **32** and flight plan **36** are also evaluated to determine if the flight plan violates a polygon (e.g. hard boundary **38**). The flight plan evaluation logic is discussed in more detail below in connection with FIGS. **10**A-**10**C. If the flight plan does not remain inside a boundary polygon, the system disables propulsion as shown at step **94**.

[0060] If the aircraft will stay inside a polygon at step **92** (or outside a polygon if the boundaries **32** include a stay-out region), the pre-flight checks then proceed to evaluate the navigation system health as shown at **72** and **74**. The propulsion system is disabled at **76**A if the navigation system is not healthy (i.e. is not operating properly). This may be accomplished by either comparing the independent positioning sources to verify that they agree within an acceptable threshold or by estimating the errors present within the position solutions and verifying that they are below an acceptable threshold. The system then assesses the power system at steps **78** and **80**, and disables propulsion at step **82**A if the power system is not functioning properly. Evaluation of the health of the Power system is discussed in more detail below in connection with FIGS. **12**A-**12**D. The output **96** of the pre-flight checks may comprise disabling propulsion or allowing propulsion. It will be understood that the output **96** may further comprise an audio and/or visual signal to the operator utilizing the graphical user interface **30**. For example, if the pre-flight checks **48** do not detect a problem, the graphical user interface **30** may provide a message indicating that the pre-flight checks have not revealed a problem, and that the unmanned aircraft **2** may proceed. However, a warning signal may also be provided if the pre-flight checks indicate a problem to alert a user concerning the nature of the problem. For example, the graphical user interface **30** may display a message indicating that the flight path will violate a boundary, that the navigation system is not operating properly, and/or that the electrical power system of the unmanned aircraft **2** is not operating properly.

[0061] Evaluation of various flight paths is shown schematically in FIGS. **10**A-**10**C. With reference to FIG. **10**A, if a flight path **36**A is within hard boundary **38** and soft boundary **44**, the system does not take any action. The flight plan **36**A of FIG. **10**A generally corresponds to a "yes" determination at step **92** (FIG. **4**A).

[0062] With reference to FIG. **10**B, if a flight path **36**B crosses soft boundary **44**, but does not cross hard boundary **38**, the system actuates a warning to the operator. The warning may comprise a message that is displayed on graphical user interface **30** (FIG. **1**), or other suitable warning to the operator. It will be understood that the flight plan warning of FIG. **10**B is not specifically shown in FIG. **4**A. However, the determination of FIG. **10**B may be implemented utilizing a second determination that is similar to the "inside polygon?" determination at step **92** following a "yes" determination at step **92**, which includes warning an operator if soft boundary **44** is violated, but still proceeding to the navigation system health evaluation **72**.

[0063] With further reference to FIG. **10**C, if a flight path **36**C crosses both hard boundary **38** and soft boundary **44**, the system **1** determines that an invalid flight plan has been entered, and the system **1** disables propulsion. FIG. **10**C generally corresponds to the steps **92** and **94** of FIG. **4**A.

[0064] With further to FIG. **5**, if the navigation systems **14** and/or **16** are not operating properly at step **74** (see also FIGS. **3** and **4**), the boundary violation prediction and detection component **22** determines what action to take at step **76**. At step **98**, the boundary violation prediction and detection component **22** determines if a navigation sensor has been lost. If not, the boundary violation prediction and detection component **22** determines at step **100** if both navigation sensors (alternative PNT system **14** and GPS system **16**, FIG. **1**) indicate a safe state. If "yes" the system triggers a warning at step **102**. If not, the boundary violation prediction and detection component **22** triggers termination at step **104**. In general, warning **102** may comprise a message displayed on graphical user interface **30**, and ter-

mination **104** may comprise halting all thrust from propulsion system **12**. If, at step **98**, it is determined that a navigation sensor **14** and/or **16** has been lost, the boundary violation prediction and detection component **22** determines if a functioning navigation system **14** or **16** indicate a safe state. If "yes," a warning is triggered as shown at **108**. If "no," termination is triggered as shown at **110**. Warning **108** may be substantially the same as warning **102**, and termination **110** may be substantially the same as termination **104**.

[0065] With further reference to FIG. **6**, at step **80** (see also FIGS. **3** and **4**), the system determines if the power system **9** is operating properly. If "no," at step **112** the boundary violation prediction and detection component **22** determines if the power system is fully compromised. If "yes," the boundary violation prediction and detection component **22** triggers termination at step **112**. If "no," the boundary violation prediction and detection component **22** triggers a warning at step **114**.

[0066] With further reference to FIG. **12**A, if the power system **9** is determined to be healthy (i.e. operating within the safe voltage range), the boundary violation prediction and detection component **22** does not take any action. In general, FIG. **12**A corresponds to normal operation of unmanned aircraft **2**. As shown in FIG. **12**B, if the voltage level V is in a range that is below the lowest safe voltage but above the highest unsafe voltage, the boundary violation prediction and detection component **22** may execute a contingency maneuver. In general, the contingency maneuver of FIG. **12**B may correspond to the warning **114** of FIG. **6**. The contingency maneuver may, for example, involve reducing thrust of propulsion system **12** and causing the unmanned aircraft **2** to land. This maneuver may be executed by auto pilot **7** (FIG. **1**) of the unmanned aircraft **2**. With reference to FIGS. **12**C and **12**D, if the voltage V is unsafe because it is either too low (FIG. **12**C) or too high (FIG. **12**D), the boundary violation prediction and detection component **22** terminates operation of unmanned aircraft **2**. Termination may involve preventing propulsion system **12** from producing any thrust. It will be understood that the safe and unsafe voltage criteria may be different for different unmanned aircraft **2**, and the invention is not limited to any specific range of voltages.

[0067] With further reference to FIGS. **7**A-**7**D, the navigation systems **14** and/or **16** may have uncertainty (error) associated with respect to the accuracy of the position of unmanned aircraft **2**. This uncertainty is shown in FIGS. **7**A-**7**D as an "error ellipse" or region **120** around unmanned aircraft **2**. It will be understood that error ellipse **120** may be a 3 dimensional (3D) region about unmanned aircraft **2** having a shape defined by the uncertainty of the unmanned aircraft **2** and this shape is not necessarily an ellipse. The lateral boundary evaluation logic for stay-in regions **40** takes into account the error ellipse **120**. More specifically, as shown in FIG. **7**A, if the error ellipse **120** is inside all boundaries (i.e. including warning boundary **46**), no action is taken. However, if the error ellipse crosses warning boundary **46** as shown in FIG. **7**B, the boundary violation prediction and detection component **22** executes a contingency maneuver. For example, the boundary violation prediction and detection component **22** may cause the auto pilot **7** to land unmanned aircraft **2** immediately. If the error ellipse **120** crosses the soft boundary **44** (FIG. **7**C) or the hard boundary **38** (FIG. **7**D), the boundary violation prediction and detection component **22** terminates operation of unmanned aircraft **2**. Termination may involve stopping all thrust of propulsion system **12**. In general, the boundary violation prediction and detection component **22** will terminate operation when the error ellipse **120** crosses the soft boundary **44** (FIG. **7**C), such that the unmanned aircraft **2** does not reach the position of FIG. **7**D in which error ellipse **120** crosses hard boundary **38**. Nevertheless, the boundary violation prediction and detection component **22** is configured to terminate operation if the error ellipse **120** does cross hard boundary **38** as shown in FIG. **7**D.

[0068] The lateral boundary evaluation logic for stay-out regions is shown in FIGS. **8**A-**8**D. In general, the logic operation of FIGS. **8**A-**8**D corresponds to the operating logic for the stay-in regions of FIGS. **7**A-**7**D, respectively. When the error ellipse **120** is outside of all boundaries (FIG. **8**A) the boundary violation prediction and detection component **22** does not take any action, and the unmanned aircraft **2** continues to operate in a normal manner. If the error ellipse **120** crosses warning boundary **46** (FIG. **8**B), the boundary violation prediction and detection component **22** causes the auto pilot **7** to execute a contingency maneuver. If the error ellipse **120** crosses the soft boundary **44** (FIG. **8**C) or the hard boundary **38** (FIG. **8**D), the boundary violation prediction and detection component **22** terminates operation of unmanned aircraft **2**.

[0069] The boundary evaluation logic for vertical boundaries is shown in FIGS. **9**A-**9**D. If the error ellipse **120** is inside all boundaries (FIG. **9**A), the boundary violation prediction and detection component **22** does not take any action, and the unmanned aircraft **2** continues to operate in a normal manner. If the error ellipse **120** crosses warning boundary **46**, the boundary violation prediction and detection component **22** executes a contingency maneuver (e.g. auto pilot **7** causes unmanned aircraft **2** to land immediately). If the error ellipse **120** crosses the soft boundary **44** (FIG. **9**C) or a hard boundary **38** (FIG. **9**D), the boundary violation prediction and detection component **22** terminates operation by shutting off all thrust of propulsion system **12**. As shown in FIGS. **9**A-**9**D, both upper and lower boundaries may be entered to limit vertical travel of the unmanned aircraft **2** in both upward and downward directions. It will be understood that only an upper boundary, only a lower boundary, or both may be entered, depending upon the circumstances (i.e. restrictions) present in the area in which the unmanned aircraft **2** is being flown.

[0070] With further reference to FIGS. **11**A-**11**D, the alternative navigation system **14** may provide a first aircraft location **2**A, and the GPS navigation system **16** may provide a second aircraft location **2**B that is not exactly the same as the position **2**A. The locations **2**A and **2**B have error boundaries that, when combined, produce an error ellipse **122**. As shown in FIG. **11**A, during normal operation the error ellipse **122** is within all boundaries (i.e. soft boundary **44** and hard boundary **38**), and the boundary violation prediction and detection component **22** takes no action such that the unmanned aircraft **2** operates in its normal manner.

[0071] With reference to FIG. **11**B if one of the navigation systems **14** or **16** is lost, such that a single aircraft location **2**A or **2**B is available, the boundary violation prediction and detection component **22** causes the auto pilot **7** to execute a contingency maneuver. The contingency maneuver may comprise landing the unmanned aircraft **2**.

[0072] With further reference to FIG. **11**C, if the positions **2**A and **2**B provided by the navigation systems **14** and **16**,

respectively, show an unacceptably high discrepancy, and if the combined error ellipse **122** is within both boundaries **44** and **38**, the boundary violation prediction and detection component **22** causes the auto pilot **7** to execute a contingency maneuver (e.g. landing unmanned aircraft **2**). However, as shown in FIG. **11**D, if the navigation systems **14** and **16** produce an unacceptable discrepancy between the aircraft positions **2**A and **2**B, and if the combined error ellipse **122** crosses soft boundary **44** (or hard boundary **38**), the boundary violation prediction and detection component **22** causes the auto pilot **7** to terminate flight by eliminating all thrust from propulsion system **12**.

What is claimed is:

1. A geo-containment system, comprising:

at least one unmanned aircraft;

a control system configured to limit flight of the unmanned aircraft based, at least in part, on pre-defined geo-spatial operational boundaries including a primary geo-spatial operational boundary and at least one secondary geo-spatial operational boundary that is spaced apart from the primary geo-spatial operational boundary at a minimum safe distance, and wherein the minimum safe distance is determined while the unmanned aircraft is in flight utilizing, at least in part: (1) state information of the unmanned aircraft including position and velocity of the unmanned aircraft, and (2) dynamics coefficients of the unmanned aircraft, and wherein:

the control system is configured to alter operation of the unmanned aircraft if the unmanned aircraft violates either the primary geo-spatial operational boundary or the secondary geo-spatial operation boundary by moving to a position in which the unmanned aircraft is less than an allowable distance from either the primary geo-spatial operational boundary or the secondary geo-spatial operational boundary.

2. The geo-containment system of claim **1**, wherein:

the control system is configured to terminate operation of the unmanned aircraft if the unmanned aircraft violates either the primary geo-spatial operational boundary or the secondary geo-spatial operation boundary by moving to a position in which the unmanned aircraft is less than an allowable distance from either the primary geo-spatial operational boundary or the secondary geo-spatial operational boundary.

3. The geo-containment system of claim **2**, wherein:

the at least one secondary geo-spatial operational boundary comprises a warning boundary and a soft boundary located between the warning boundary and the primary geo-spatial operational boundaries;

the soft boundary is at the minimum safe distance from the primary geo-spatial operational boundary.

4. The geo-containment system of claim **3**, wherein:

the warning boundary is spaced apart from the primary geo-spatial operational boundary a distance that is equal to a scale factor times the minimum safe distance.

5. The geo-containment system of claim **4**, wherein:

the control system is configured to generate a warning signal if the unmanned aircraft crosses the warning boundary.

6. The geo-containment system of claim **5**, wherein:

the unmanned aircraft includes a control system that causes the unmanned aircraft to perform a contingency maneuver if a warning signal is generated by the control system.

7. The geo-containment system of claim **6**, wherein:

the contingency maneuver includes causing the unmanned aircraft to: 1) turn; and/or 2) reduce altitude; and/or 3) reduce speed.

8. The geo-containment system of claim **1**, wherein:

the unmanned aircraft includes a first navigation system that is GPS-based, and a second navigation system that is GPS-independent.

9. The geo-containment system of claim **8**, wherein:

the first navigation system provides a position of the unmanned aircraft during flight that is accurate to within a first error distance;

the second navigation system provides a position of the unmanned aircraft during flight that is accurate to within a second error distance; and

the allowable distance comprises the greater of the first and second error distances.

10. The geo-containment system of claim **8**, wherein:

the second navigation system comprises a local positioning system that utilizes a plurality of ground-based beacons to determine a position of the unmanned aircraft in flight.

11. The geo-containment system of claim **1**, wherein:

the geo-spatial operational boundaries comprise at least one of a stay-in region and a stay-out region.

12. The geo-containment system of claim **2**, wherein:

the unmanned aircraft includes a propulsion system that provides thrust; and

the control system terminates operation of the unmanned aircraft by reducing the thrust of the propulsion system.

13. The geo-containment system of claim **1**, wherein:

the geo-containment system is configured to receive and evaluate a flight plan prior to flight of the unmanned aircraft;

the geo-containment system is configured to determine if the flight plan will cause the unmanned aircraft to violate at least one of the primary geo-spatial operational boundary and the secondary geo-spatial operational boundary.

14. The geo-containment system of claim **13**, wherein:

the unmanned aircraft includes a propulsion system; and

the geo-containment system is configured to disable the propulsion system if the flight plan will cause the unmanned aircraft to violate at least one of the primary geo-spatial operational boundary and the secondary geo-spatial operational boundary.

15. The geo-containment system of claim **1**, wherein:

the primary geo-spatial operational boundary comprises a two-dimensional polygon defining at least one of a lateral boundary and a vertical boundary.

16. A method of controlling an unmanned aircraft, the method comprising:

providing at least one unmanned aircraft;

providing a primary geo-spatial operational boundary;

determining at least one secondary geo-spatial operational boundary that is spaced apart from the primary geo-spatial operational boundary at a minimum safe distance, wherein the minimum safe distance is determined while the unmanned aircraft is in flight utilizing,

at least in part: (1) state information of the unmanned aircraft including position and velocity of the unmanned aircraft, and (2) dynamics coefficients of the unmanned aircraft, and:

altering operation of the unmanned aircraft if: (1) the unmanned aircraft crosses either the primary geo-spatial operational boundary or the secondary geo-spatial operation boundary; or (2) the unmanned aircraft moves to a position in which the unmanned aircraft is less than an allowable distance from either the primary geo-spatial operational boundary or the secondary geo-spatial operational boundary.

17. The method of claim **16**, including:

terminating operation of the unmanned aircraft if the unmanned aircraft violates either the primary geo-spatial operational boundary or the secondary geo-spatial operation boundary by moving to a position in which the unmanned aircraft is less than an allowable distance from either the primary geo-spatial operational boundary or the secondary geo-spatial operational boundary.

18. The method of claim **17**, including:

determining a location of a warning boundary, wherein the warning boundary is spaced apart from the primary geo-spatial operational boundary a distance that is greater than the minimum safe distance.

19. The method of claim **18**, including:

generating a warning signal and/or causing the unmanned aircraft to perform a contingency maneuver if the unmanned aircraft crosses the warning boundary, wherein the contingency maneuver includes turning and/or reducing altitude and/or reducing speed.

20. The method of claim **16**, including:

evaluating a flight plan prior to flight of the unmanned aircraft to determine if the flight plan will cause the unmanned aircraft to violate at least one of the primary geo-spatial operational boundary and the secondary geo-spatial operational boundary; and

generating a warning and/or at least partially disabling the unmanned aircraft if the flight plan will cause the unmanned aircraft to violate at least one of the primary geo-spatial operational boundary and the secondary geo-spatial operational boundary.

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