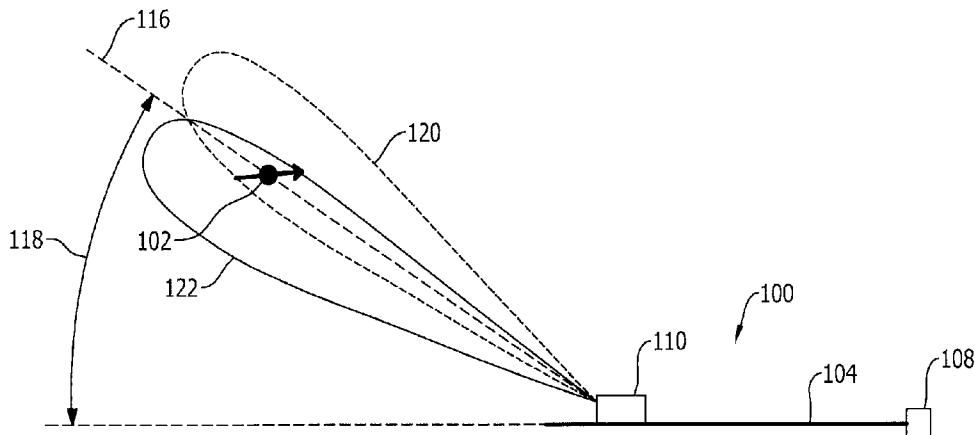




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 (54) Title: FLIGHT CONTROL SYSTEM WITH SYNTHETIC INERTIAL GLIDESLOPE DEVIATION AND METHOD OF
 USE



(57) **Abrégé/Abstract:**

A flight control module for computing glideslope deviation during landing of an aircraft is provided. The flight control module includes a communication interface and a processor. The communication interface is configured to receive inertial data for the aircraft. The processor is coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data.

ABSTRACT

A flight control module for computing glideslope deviation during landing of an aircraft is provided. The flight control module includes a communication interface and a processor. The communication interface is configured to receive inertial data for the aircraft. The processor is coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data.

**FLIGHT CONTROL SYSTEM WITH SYNTHETIC
INERTIAL GLIDESLOPE DEVIATION AND METHOD
OF USE**

BACKGROUND

The field of the disclosure relates generally to flight control systems and, more specifically, to a flight control module utilizing a synthetic inertial glideslope deviation.

5 Many known aircraft feature an automated landing system that controls the aircraft during landing. Automated landing systems have become increasingly more common and are frequently relied on for both instrument landings under instrument flight rules (IFR) and landings performed under visual flight rules (VFR). Known automated landing systems utilize various receivers, such as multi-mode receivers (MMRs), for example, to receive guidance signals transmitted from the ground. Such
10 guidance signals may include, for example, instrument landing system (ILS) signals, global positioning service (GPS) landing system (GLS) signals, and/or microwave landing system (MLS) signals. The guidance signals inform the aircraft of its position relative to a desired vertical and lateral path to the runway and through roll-out after touchdown. The desired vertical path is referred to as the glideslope and the lateral
15 path is referred to as the localizer. The glideslope is typically defined as a **3°** descent with a desired intercept with the ground at **1000** feet beyond the runway threshold. The localizer guides the aircraft to the runway centerline.

The guidance signals transmitted from the ground are received by an on-board antenna and routed to redundant MMRs. Each MMR computes a localizer
20 deviation and a glideslope deviation that are routed to a flight control module that includes the automated landing system. The localizer deviation is an indication of the aircraft's position relative to the desired path to the runway centerline. For example, the localizer deviation may indicate the aircraft is approximately **2°** left of the runway centerline. The glideslope deviation is an indication of the aircraft's position relative
25 to the desired glideslope to the runway. For example, the glideslope deviation may

indicate the aircraft is 1° below the desired glideslope. The flight control module uses the localizer deviation and the glideslope deviation to adjust the automated landing system and to command control surfaces of the aircraft.

5 Many known automated landing systems require three independently computed localizer and glideslope deviations. Such redundancy ensures that if one localizer deviation or one glideslope deviation fails, the automated landing system still has two good signals to control the aircraft. The redundant equipment necessary for independently computing three localizer and glideslope deviations adds cost and weight to the aircraft. If the available localizer deviation and glideslope deviations
10 disagree beyond a predetermined threshold, the automated landing system forfeits control of the aircraft to the pilot. The availability of reliable, i.e., “good,” localizer deviation and glideslope deviation signals is particularly important when the aircraft descends below 200 feet, because the margins for error are tighter and errant control by the automated landing system may result in the aircraft missing the runway.
15 Accordingly, when failures or erroneous localizer or glideslope signals are detected, the flight control system relies on the good localizer and glideslope signals or forfeits control to the pilot.

BRIEF DESCRIPTION

20 In one embodiment, there is provided a flight control module for computing glideslope deviation during landing of an aircraft. The module comprises a communication interface coupled to a radar altimeter and configured to receive first and second glideslope deviation signals indicative of respective glideslope deviations computed based on a glideslope transmission received by the aircraft, an altitude of the aircraft measured by the radar altimeter, and inertial data for the aircraft. The
25 modules further includes a processor coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data when the altitude falls below a predetermined threshold and a signal selection fault detection (SSFD) module configured to select one glideslope deviation from among the respective glideslope deviations when the aircraft is operating above the

predetermined threshold, and from among the respective glideslope deviations and the inertial glideslope deviation when the aircraft is operating below the predetermined threshold, wherein the selected glideslope deviation is for use in controlling an automated landing system of the aircraft.

5 In another embodiment there is provided a flight control system for landing an aircraft. The flight control system includes a communication bus and first and second multi-mode receivers (MMRs) coupled to the communication bus and configured to compute first and second glideslope deviations based on received glideslope signals, and transmit first and second glideslope deviation signals indicative of the first and
10 second glideslope deviations onto the communication bus. The flight control system further includes a flight control module coupled to the communication bus and configured to: receive inertial data for the aircraft and the first and second glideslope deviation signals over the communication bus, initialize an inertial glideslope deviation computation when an altitude of the aircraft falls below a predetermined altitude,
15 compute an inertial glideslope deviation based on the inertial data, select one glideslope deviation from among the first and second glideslope deviations and the inertial glideslope deviation, and transmit the one glideslope deviation to an automated landing system for the aircraft.

 In another embodiment, there is provided a method of detecting a glideslope
20 deviation for an aircraft during landing. The method involves receiving first and second instrument landing system (ILS) glideslope signals, computing first and second multi-mode receiver (MMR) glideslope deviations with respect to a main landing gear of the aircraft based on the ILS glideslope signals, filtering the first and second MMR glideslope deviations, translating a filtered MMR glideslope deviation from the main
25 landing gear to a guidance control point (GCP) for the aircraft, initializing an inertial glideslope deviation computation based on the filtered MMR glideslope deviation when an altitude of the aircraft falls below a predetermined threshold, integrating inertial data, generated by an inertial reference unit (IRU) for the aircraft, from the filtered MMR glideslope deviation to generate an inertial

glideslope deviation with respect to the IRU and translating the inertial glideslope deviation from the IRU to the GCP.

In another embodiment there is provided a flight control module for computing glideslope deviation during landing of an aircraft. The flight control module includes a communication interface configured to receive inertial data for the aircraft and first and second multi-mode receiver MMR glideslope deviation signals indicative of respective glideslope deviations computed based on a glideslope transmission received by the aircraft and an altitude of the aircraft measured by a radar altimeter. The module further includes a processor coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data and a filtered MMR glideslope deviation when the altitude falls below a predetermined threshold. The flight control module further includes a signal selection fault detection SSFD module configured to select, when the altitude is below the predetermined threshold, one glideslope deviation from among the respective glideslope deviations and the inertial glideslope deviation for use in controlling an automated landing system of the aircraft.

In another embodiment there is provided method of detecting a glideslope deviation for an aircraft during landing, the aircraft receiving first and second instrument landing system, ILS, glideslope signals and computing first and second multi-mode receiver, MMR, glideslope deviation signals with respect to a main landing gear of the aircraft based on the first and second ILS glideslope signals. The method involves receiving inertial data for the aircraft, receiving the first and second MMR glideslope deviation signals indicative of respective glideslope deviations, filtering the first and second MMR glideslope deviations to obtain a filtered MMR glideslope deviation, translating the filtered MMR glideslope deviation from the main landing gear to a guidance control point (GCP) for the aircraft, initializing an inertial glideslope deviation computation based on the filtered MMR glideslope deviation when an altitude of the aircraft falls below a predetermined threshold, integrating the inertial data, generated by an inertial reference unit (IRU) for the aircraft, from the filtered

MMR glideslope deviation to generate an inertial glideslope deviation with respect to the IRU, translating the inertial glideslope deviation from the IRU to the GCP and selecting one glideslope deviation from among the respective first and second glideslope deviations and the inertial glideslope deviation for use in controlling an automated landing system of the aircraft.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top perspective diagram of an exemplary instrument landing system (ILS) for use in landing an aircraft;

FIG. 2 is a side perspective diagram of the exemplary ILS shown in FIG. 1;

FIG. 3 is a side perspective diagram of the aircraft shown in FIGS. 1 and 2
5 during landing;

FIG. 4 is block diagram of an exemplary flight control system for the aircraft shown in FIGS. 1-3;

FIG. 5 is a functional block diagram of an exemplary flight control module for use in the flight control system shown in FIG. 4; and

FIG. 6 is a flow diagram of an exemplary method of detecting a glideslope deviation for use in the flight control system shown in FIG. 4.
10

DETAILED DESCRIPTION

As used herein, an element or step recited in the singular and proceeded with the word “a” or “an” should be understood as not excluding plural elements or steps
15 unless such exclusion is explicitly recited. Furthermore, references to “one embodiment” of the present invention or the “exemplary embodiment” are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

FIG. 1 is a perspective diagram, from a top-view, of an exemplary instrument
20 landing system (ILS) **100** for use in landing an aircraft **102**. FIG. 2 is another perspective diagram, from a side view, of ILS **100**. Aircraft **102** is illustrated during approach for landing on a runway **104**. Runway **104** is characterized by a runway centerline **106** that extends towards and beyond aircraft **102** for illustrative purposes.

Referring to FIG. 1, in the exemplary embodiment, ILS **100** includes a localizer transmitter **108** and a glideslope transmitter **110**. Localizer transmitter **108** transmits a first localizer beam **112** and a second localizer beam **114** towards aircraft **102**. First localizer beam **112** and second localizer beam **114** cooperate define an ILS localizer signal that is received by aircraft **102** and processed to generate localizer deviations indicative of the lateral position of aircraft **102** relative to runway centerline **106**. The localizer signals are typically used to control aircraft **102** through landing and rollout, i.e., deceleration along runway prior to taxi.

Referring to FIG. 2, aircraft **102** approaches runway **104** along a predefined glideslope **116** that intercepts runway **104** at a predefined distance beyond a runway threshold for runway **104**. The predefined distance is typically, for example, at least **1000** feet from the runway threshold, which is typically the site of glideslope transmitter **110**. Glideslope **116** is defined by a glideslope angle **118** measured between glideslope **116** and runway **104**. A typical glideslope, for example, is defined by glideslope angle **118** being equal to approximately **3°**. Glideslope transmitter **110** transmits a first glideslope beam **120** and a second glideslope beam **122** towards aircraft **102**. First glideslope beam **120** and second glideslope beam **122** define an ILS glideslope signal that is received by aircraft **102** and that is processed to generate glideslope deviations indicative of the vertical position of aircraft **102** relative to glideslope **116**. The glideslope signals are typically used to control aircraft **102** until it reaches a flare altitude, i.e., an altitude when the nose of aircraft **102** pitches up prior to landing, which typically occurs between **50** and **75** feet. When the flare altitude is reached, aircraft **102** typically switches to a radio altimeter to guide aircraft **102** to runway **104** for landing. In alternative embodiments, flare altitude may be greater than **75** feet or, in some embodiments, below **50** feet.

FIG. 3 is a perspective diagram of aircraft **102** during landing. FIG. 3 illustrates a side-view of aircraft **102** approaching runway **104** during the landing process. Aircraft **102** includes a guidance control point (GCP) **302** to which all flight control commands for aircraft **102** are referenced. GCP **302** is typically located at the

nose of aircraft **102**. Aircraft **102** also includes an inertial reference unit (IRU) **304** that includes various sensors for detecting linear and angular accelerations of aircraft **102**, which are translatable to accelerations, velocities, and attitude of aircraft **102** along three axis, i.e., pitch, roll, and yaw. IRU **304** is typically located at or near
5 the center of aircraft **102**, which is illustrated in FIG. **3** as the intersection of the wings **305** and fuselage **307** of aircraft **102**. Accordingly, GCP **302** and IRU **304** are typically separated by a distance **306** extending along a portion of the length of fuselage **307** of aircraft **102**.

Aircraft **102** approaches runway **104** following glideslope **116**, which is
10 defined by glideslope angle **118** with respect to the plane of runway **104**. Glideslope **116** meets runway **104** at an intercept **308**. Aircraft **102** is traveling at a ground speed **310** and with a vertical velocity **312**. Ground speed **310** and vertical velocity **312** are both measurable at IRU **304** and define a velocity vector **314**. Vertical velocity **312** includes two components: a glide path rate **316** and a glideslope error
15 rate **318**. Given inertial accelerations measured by IRU **304** and glideslope **116**, aircraft **102** may compute inertial vertical velocity **312** that, over time, increases or decreases a glideslope deviation.

Aircraft **102** operates with a degree of pitch attitude, or simply pitch **320**.
Consequently, GCP **302** is generally elevated with respect to IRU **304**. The vertical
20 correction to GCP **322** is a function of pitch **320** and distance **306**. Moreover, MMR glideslope deviation calculations are referenced at main landing gear **324** of aircraft **102**, which require further translation to account for a vertical correction **326** from main landing gear **324** to GCP **302**.

FIG. **4** is block diagram of an exemplary flight control system **400** for aircraft
25 **102**, shown in FIGS. 1-3. Flight control system **400** includes a flight control module **402** that controls aircraft **102** by transmitting commands to an actuator control module **404**. Flight control module **402** communicates with actuator control module **404** over a communication bus **406**. Actuator control module **404** controls one or more actuators **408** that are attached to various flight control surfaces of aircraft **102**.

Actuator control module **404** communicates with actuators **408** over a communication bus **410**.

Aircraft **102** includes various sensors **412** that measure flight parameters and generate data that is transmitted onto a communication bus **414**. Flight control module **402** is communicably coupled to communication bus **414** through communication interface **415** and gains access to the data.

Sensors **412** include various accelerometers and gyroscopes located at IRU **304** that provide vertical velocity **312**, ground speed **310**, and pitch **320**. Communication bus **414** is configured to be coupled to IRU **304**, which provides the inertial data. Communication bus **414** is further coupled to various other data sources, such as a navigation system (not shown), a flight management system (not shown) that provides vertical velocity **416** and vertical acceleration **417** referenced to landing gear **324**, and a radar altimeter **418** that provides altitude for aircraft **102**. Communication bus **414** is further coupled to a left MMR **420** and a right MMR **422**. Left MMR **420** provides a left MMR glideslope deviation **424**. Right MMR **422** provides a right MMR glideslope deviation **426**.

Communication interface **415** receives first and second glideslope deviation signals indicative of respective glideslope deviations, such as left MMR glideslope deviation **424** and right MMR glideslope deviation **426**, computed based on the glideslope transmission received by aircraft **102**.

Flight control module **402** includes an automated landing system **428**. Flight control module **402** receives and processes data from communication bus **414** to produce a glideslope deviation signal that is used by automated landing system **428** to generate commands for actuator control module **404**. Flight control module **402** receives left MMR glideslope deviation **424** and right MMR glideslope deviation **426** expressed in difference in the depth of modulation (ddm). Flight control module **402** includes amplifiers **430** and **432** that each apply a gain, $K_{\text{ddm-degrees}}$, to the ddm

values to convert left MMR glideslope deviation **424** and right MMR glideslope deviation **426** to degrees.

Flight control module **402** includes a synthetic inertial glideslope deviation module (SIGD) processor **434** that computes an inertial glideslope deviation **436**, also referred to as a SIGD, based on data received over communication bus **414**. Inertial glideslope deviation **436** is converted from feet to degrees by an amplifier **438** that applies a gain, $K_{\text{feet-degrees}}$. Flight control module **402** selects which glideslope signal to use to command actuator control module **404** using a signal selection fault detection (SSFD) algorithm. Flight control module **402** includes a mid-value selector **440** for carrying out SSFD. Mid-value selector **440** is sometimes referred to as an SSFD module, which is configured to select one glideslope deviation from among MMR glideslope deviations **424** and **426**, and inertial glideslope deviation **436** for use in controlling automated landing system **428** of aircraft **102**. Mid-value selector **440** selects a middle value from among left MMR glideslope deviation **424**, right MMR glideslope deviation **426**, and inertial glideslope deviation **436**. The selected glideslope deviation **444** is converted from degrees to feet by an amplifier **442** and fed back to SIGD processor **434**. SIGD processor **434** complementary-filters the selected glideslope deviation and generates a complementary-filtered glideslope deviation **446**.

The addition of inertial glideslope deviation **436** enables continued use of automated landing system **428** in the event of an undetected failure in one of left MMR **420** and right MMR **422** below an alert height, or altitude. Typically, the alert height is **200** feet. If one of left MMR glideslope deviation **424** and right MMR glideslope deviation **426** fails and is not respectively detected by left MMR **420** or right MMR **422**, mid-value selector **440** detects the failure as the failed signal will be different from the two good signals. Generally, known systems utilize three MMRs, which add weight and cost to aircraft **102**. When the two remaining good glideslope deviation signals mis-compare, automated landing system **428** disengages and forfeits control of aircraft **102** to the pilot. Other known systems utilize two self-

monitoring MMRs. In the event of an undetected failure in left MMR glideslope deviation **424** or right MMR glideslope deviation **426**, the two signals mis-compare, but no third signal is available. Such a failure results in automated landing system **428** disengaging. Inertial glideslope deviation **436** introduces a third glideslope signal that enables flight control module **402** to withstand an undetected failure in one of left MMR glideslope deviation **424** or right MMR glideslope deviation **426**.

Flight control module **402** may be embodied on one or more processors. Likewise, SIGD processor **434**, mid-value selector **440**, and automated landing system **428** may be embodied on one or more processors configured to carry out the functionality described above.

FIG. **5** is a functional block diagram of flight control module **402** and, more specifically, SIGD processor **434**, shown in FIG. **4**. SIGD processor **434** includes a complementary filter **502**, a translation block **504**, a glideslope computation block **506**, an inertial glideslope error rate block **508**, and a translation-to-GCP block **510**.

Complementary filter **502** blends high-frequency content of inertial data from IRU **304** with low-frequency content of left MMR glideslope deviation **424** and right MMR glideslope deviation **426** to produce a smooth, complementary-filtered glideslope deviation **446**. Complementary filter **502** generally operates in terms of feet. Complementary-filtered glideslope deviation **446**, expressed in feet, is fed back and subtracted **512** from selected glideslope deviation **444** to produce a glideslope deviation error value. Mid-value selector **440** operates in terms of degrees or radians. Accordingly, selected glideslope deviation **444** is converted to feet by gain **442** prior to use by complementary filter **502** to compute the glideslope deviation error value. The glideslope deviation error value is gained by K_3 and integrated **514**. The result of integration **514** is added **516** to vertical acceleration **417**, and then added **518** to the glideslope deviation error value gained **520** by K_2 . The result of summing **518** is integrated **522** and added **524** to vertical velocity **416**, the result of which is added **526** to the glideslope deviation error value gained **528** by K_1 . The result of summation **526** is integrated **530** to generate complementary-filtered

glideslope deviation **446**, which is referenced to landing gear **324**. Complementary filter **502** is further characterized by, but not limited to the following equation, where D_{CF} is complementary-filtered glideslope deviation **446** as a function of time, t , and expressed in feet, D_{sel} is selected glideslope deviation **444** as a function of time, t , and expressed in feet, A_{vert} is vertical acceleration **417** as a function of time, t , and V_{vert} is vertical velocity **416** as a function of time, t .

$$D_{CF} = \left[\frac{K_1 S^2 + K_2 S + K_3}{S^3 + K_1 S^2 + K_2 S + K_3} \right] \times D_{sel} + \left[\frac{S}{S^3 + K_1 S^2 + K_2 S + K_3} \right] \times A_{vert} + \left[\frac{S^2}{S^3 + K_1 S^2 + K_2 S + K_3} \right] \times V_{vert} \quad \text{EQ. 1}$$

When aircraft **102** descends, as measured by radar altimeter **418**, below an altitude threshold **532**, complementary-filtered glideslope deviation **446** is latched **534** as an initial condition for integration **536** of inertial glideslope error rate **318**. Aircraft altitude from radar altimeter **418** is compared **536** to altitude threshold **532**, e.g., **200** feet, to trigger latch **534**. Latch **534** prevents toggling due to variations in radar altimeter **418** due to terrain leading up to runway **104**, i.e., terrain between aircraft **102** and runway **104**.

Translation block **504** translates complementary-filtered glideslope deviation **446** from landing gear **324** to GCP **302**. Translation block **504** computes a correction **326** that includes two components: an X component **540** and a Z component **542**, the two of which are summed **544** to yield correction **326**. Correction **326** is then summed **546** with complementary-filtered glideslope deviation **446**, completing the translation from landing gear **324** to GCP **302**.

X component **540** is the projection of a distance, X_{GCP-LG} , along a portion of fuselage **307** between main landing gear **324** and GCP **302**. The projection is computed as the sine **548** of pitch **320**, the result of which is gained **550** by the distance, X_{GCP-LG} . Z component **542** is similarly the projection of a vertical distance, Z_{GCP-LG} , between main landing gear **324** and GCP **302**. The projection is computed as the cosine **552** of pitch **320**, the result of which is gained **554** by the distance,

Z_{GCP-LG} . Translation block **504** is further characterized by, but not limited to, the following equation, where C_{GCP-LG} is correction **326** as a function of time, t , and Att_{pitch} is pitch **320** as a function of time, t .

$$5 \quad C_{GCP-LG}(t) = X_{GCP-LG} \times \sin(Att_{pitch}(t)) + Z_{GCP-LG} \times \cos(Att_{pitch}(t)) \quad \text{EQ. 2}$$

Inertial glideslope error rate block **508** computes an error rate **556** based on an average glideslope angle **558**, ground speed **310**, and vertical velocity **312**. Error rate is computed as a difference **560** between vertical velocity **312** and desired glideslope rate **316**. Glideslope rate **316** is computed as an arc length, i.e., the multiplication **562** of average glideslope angle **558** and ground speed **310**. Inertial glideslope error rate block **508** is further characterized by, but not limited to, the following equation, where R_{error} is error rate **556** as a function of time, t , S_{gnd} is ground speed **310** as a function of time, t , and avg_{GP} is average glideslope angle **558** as a function of time, t , and expressed in radians.

$$15 \quad R_{error}(t) = V_{vert}(t) - S_{gnd}(t) \times avg_{GP}(t) \quad \text{EQ. 3}$$

Glideslope computation block **506** computes average glideslope angle **558** as a function of ground speed **310** and vertical velocity **312**. Average glideslope angle **558** is a running time-average computed as an integral **564** of inertial altitude rate, i.e., vertical velocity **312**, divided **566** by ground speed **310**. Integral **564** is then divided **568** by elapsed time **570**. Integral **564** is initialized **572** to zero once aircraft **102** is stabilized on glideslope **116**. Stability on glideslope **116** is indicated by a logical indicator **574** that is sometimes referred to as "Vert App Active." Elapsed time **570** is an integral of a time delta **576** and is initialized **578** to zero. Glideslope computation block **506** is further characterized by, but not limited to, the following equation, where t_{stable} the time at which logical indicator **574** indicates aircraft **102** is has stabilized on glideslope **116**.

$$avg_{GP}(t) = \frac{\int_{t_{stable}}^t \frac{V_{vert}}{S_{gnd}} \delta t}{\int_{t_{stable}}^t \delta t} \quad \text{EQ. 4}$$

When aircraft **102** descends below altitude threshold **532**, integrator **536** is initialized to complementary-filtered glideslope deviation **446**, which represents the glideslope deviation at that altitude. Integrator **536** then integrates error rate **556**, which is based on inertial data, to compute inertial glideslope deviation **436**. Integration **536** is further characterized by, but not limited to, the following equation, where *SIGD* is inertial glideslope deviation **436** with respect to IRU **304** as a function of time, *t*, and expressed in radians, and *t*₂₀₀ is the time at which aircraft **102** descends to altitude threshold **532**, or **200** feet, for example.

$$SIGD(t) = \int_{t_{200}}^t R_{error} \delta t \quad \text{EQ. 5}$$

Integration **536** yields inertial glideslope deviation **436** with respect to IRU **304**. A compensation **580** is added **582** to inertial glideslope deviation **436** to correct for the difference between inertial glideslope deviation **436** at IRU **304** and inertial glideslope deviation **436** at GCP **302**. Compensation **580** accounts for any pitch attitude changes that occur below altitude threshold **532**.

Translation-to-GCP block **510** computes compensation **580** as a function of pitch **320** and distance **306** along a portion of fuselage **307** between IRU **304** and GCP **302**. Distance **306** is multiplied **588** by the sine **590** of pitch **320**, yielding compensation **580** as a function of time, *t*. When aircraft **102** descends to altitude threshold **532**, the vertical difference between IRU **304** and GCP **302** due to pitch **320** is latched **584** and subtracted **586** from compensation **580** at time, *t*. Translation-to-GCP block **510** is further characterized, but not limited to, the following equation, where *C* is compensation **580** as a function of time, *t*, *L*_{IRU-GCP} is distance **306** along the fuselage of aircraft **102** between IRU **304** and GCP **302**, *Att*_{pitch} is pitch **320** as a function of time, *t*.

$$C(t) = L_{IRU-GCP} \left[\sin \left(Att_{pitch}(t) \right) - \sin \left(Att_{pitch}(t_{200}) \right) \right] \quad \text{EQ. 6}$$

FIG. 6 is a flow diagram of an exemplary method 600 of detecting a glideslope deviation for use in flight control system 400, shown in FIG. 4, of aircraft 102, shown in FIGS. 1-3. Method 600 begins with aircraft 102 receiving 610 ILS glideslope signals defined by first and second glideslope beams 120 and 122. An antenna for receiving first and second glideslope beams 120 and 122 is typically located in the nose of aircraft 102. The received signals are then passed to left MMR 420 and right MMR 422. Left MMR 420 and right MMR 422 respectively compute 620 MMR glideslope deviations 424 and 426 based on the received ILS glideslope signals. MMR glideslope deviations 424 and 426 are transmitted onto a communication bus 414, such as an ARINC-429 bus, for example.

Flight control module 402 gains access to MMR glideslope deviations 424 and 426 on communication bus 414 through communication interface 415, which may include an ARINC-429 interface circuit card configured to communicate within flight control module 402 using peripheral component interconnect (PCI), PCI Express, PC/104, Ethernet, compact PCI, or other suitable protocol. SIGD processor 434 receives MMR glideslope deviations 424 and 426 and filters 630 them using complementary filter 502 to produce complementary-filtered glideslope deviation 446. Complementary-filtered glideslope deviation 446 is computed with respect to main landing gear 324 of aircraft 102. Complementary-filtered glideslope deviation 446 is translated 640 to GCP 302.

When aircraft 102 descends to altitude threshold 532, the inertial glideslope deviation computation is initialized 650 based on complementary-filtered glideslope deviation 446, which provides the initial condition for integration 536 of glideslope error rate 556. Inertial data is integrated 660 to generate inertial glideslope deviation 436 with respect to IRU 304. Inertial data includes pitch 320, ground speed 310, and vertical velocity 312, which are all determinable based on measurements at IRU 304.

Inertial glideslope deviation **436** is translated **670** from IRU **304** to GCP **302** using translation-to-GCP block **510**, which accounts for changes in pitch **320** that occur below altitude threshold **532**.

5 The above described embodiments of flight control systems for use by an aircraft during landing provide an inertial glideslope deviation that is considered in combination with MMR glideslope deviation signals when commanding an automated landing system. More specifically, the inertial glideslope deviation provides assurance the automated landing system can continue an automated landing in the event of an undetected MMR glideslope deviation failure. The flight
10 control systems described herein and, more specifically, flight control modules, generate the inertial glideslope deviation by integrating inertial data from the aircraft's IRU from an initial condition established based on the MMR glideslope deviations.

15 Exemplary embodiments of methods, systems, and apparatus for flight control systems are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. For example, the methods may also be used in combination with other non-conventional flight control systems, and are not limited to practice with only the systems and methods
20 as described herein. Rather, the exemplary embodiment can be implemented and utilized in connection with many other applications, equipment, and systems that may benefit from increased efficiency, reduced operational cost, and reduced capital expenditure.

25 An exemplary technical effect of the methods, systems, and apparatus described herein includes at least one of: (a) generation of a SIGD for consideration in SSFD processes; (b) controlling an automated landing system based on a SIGD; (c) improving reliability of automated landing systems through addition of an inertial glideslope deviation; (d) improving failure detection in MMR glideslope deviation signals; (e) reducing cost and weight of producing triple-redundant glideslope

deviation for automated landing systems through elimination of a third MMR device; and (f) improving glideslope accuracy for automated landing systems.

Some embodiments involve the use of one or more electronic or computing devices. Such devices typically include a processor, processing device, or controller, such as
5 a general purpose central processing unit (CPU), a graphics processing unit (GPU), a microcontroller, a reduced instruction set computer (RISC) processor, an application specific integrated circuit (ASIC), a programmable logic circuit (PLC), a field programmable gate array (FPGA), a digital signal processing (DSP) device, and/or any other circuit or processing device capable of executing the functions
10 described herein. The methods described herein may be encoded as executable instructions embodied in a computer readable medium, including, without limitation, a storage device and/or a memory device. Such instructions, when executed by a processing device, cause the processing device to perform at least a portion of the methods described herein. The above examples are exemplary only, and thus are
15 not intended to limit in any way the definition and/or meaning of the terms processor, processing device, and controller.

In the embodiments described herein, memory may include, but is not limited to, a computer-readable medium, such as a random access memory (RAM), and a computer-readable non-volatile medium, such as flash memory. Alternatively, a
20 floppy disk, a compact disc – read only memory (CD-ROM), a magneto-optical disk (MOD), and/or a digital versatile disc (DVD) may also be used. Also, in the embodiments described herein, additional input channels may be, but are not limited to, computer peripherals associated with an operator interface such as a mouse and a keyboard. Alternatively, other computer peripherals may also be used that may
25 include, for example, but not be limited to, a scanner. Furthermore, in the exemplary embodiment, additional output channels may include, but not be limited to, an operator interface monitor.

This written description uses examples to disclose various embodiments, which include the best mode, to enable any person skilled in the art to practice those

embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A flight control module for computing glideslope deviation during landing of an aircraft, comprising:

a communication interface coupled to a radar altimeter and configured to receive:

5 first and second glideslope deviation signals indicative of respective glideslope deviations computed based on a glideslope transmission received by the aircraft,

an altitude of the aircraft measured by the radar altimeter, and

inertial data for the aircraft;

10 a processor coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data when the altitude falls below a predetermined threshold; and

15 a signal selection fault detection (SSFD) module configured to select one glideslope deviation from among the respective glideslope deviations when the aircraft is operating above the predetermined threshold, and from among the respective glideslope deviations and the inertial glideslope deviation when the aircraft is operating below the predetermined threshold, wherein the selected glideslope deviation is for use in controlling an automated landing system of the aircraft.

- 20 **2.** The flight control module of claim **1**, wherein the SSFD module comprises a mid-value selector configured to select a middle value from among the respective glideslope deviations and the inertial glideslope deviation.

3. The flight control module of claim 1, wherein the processor comprises a complementary filter configured to generate a filtered glideslope deviation based on a glideslope deviation signal received through the communication interface and the inertial data, including a vertical acceleration and a vertical velocity.
- 5 4. The flight control module of claim 3, wherein the communication interface is configured to be coupled to an inertial reference unit (IRU) through a communication bus, the IRU comprising a ground speed sensor, a pitch sensor, a vertical velocity sensor, and a vertical acceleration sensor, and wherein the inertial data includes a ground speed, a pitch angle, the vertical velocity, and the vertical acceleration.
- 10 5. The flight control module of claim 4, wherein the processor is further configured to initialize integration of the inertial glideslope deviation based on the filtered glideslope deviation from the complementary filter when the altitude falls below the predetermined threshold.
- 15 6. The flight control module of claim 5, wherein the processor is further configured to:
- compute an inertial glideslope error with respect to the IRU based on the ground speed, the vertical velocity, and an average glideslope angle computed based on the ground speed and the vertical velocity; and
- 20 apply a correction to the inertial glideslope error to generate the inertial glideslope deviation, the correction computed based on the pitch angle and a distance between the IRU and a guidance control point of the aircraft.
7. A flight control system for landing an aircraft, the flight control system comprising:
- 25 a communication bus;

first and second multi-mode receivers (MMRs) coupled to the communication bus and configured to:

compute first and second glideslope deviations based on received glideslope signals, and

5 transmit first and second glideslope deviation signals indicative of the first and second glideslope deviations onto the communication bus; and

a flight control module coupled to the communication bus and configured to:

10 receive inertial data for the aircraft and the first and second glideslope deviation signals over the communication bus,

initialize an inertial glideslope deviation computation when an altitude of the aircraft falls below a predetermined altitude,

compute an inertial glideslope deviation based on the inertial data,

15 select one glideslope deviation from among the first and second glideslope deviations and the inertial glideslope deviation, and

transmit the one glideslope deviation to an automated landing system for the aircraft.

8. The flight control system of claim 7 further comprising an actuator control
20 module coupled to the automated landing system through a second communication bus, the actuator control module communicably coupled to a flight control actuator, the automated landing system configured to instruct the actuator control module according to the one glideslope deviation.

- 5
9. The flight control system of claim 7 further comprising a radar altimeter configured to detect the altitude of the aircraft, the radar altimeter coupled to the communication bus, wherein the flight control module is further configured to initiate integration of the inertial data when the altitude falls below the predetermined threshold.
10. The flight control system of claim 9, wherein the flight control module is further configured to compute the inertial glideslope deviation when the altitude falls below the predetermined threshold of **200** feet.
- 10 11. The flight control system of claim 9, wherein the flight control module is further configured to select a mid-value from among the first and second glideslope deviations and the inertial glideslope deviation as the one glideslope deviation for transmission to the automated landing system.
- 15 12. The flight control system of claim 9, wherein the flight control module is further configured to initialize computation of the inertial glideslope deviation based on at least one of the first and second glideslope deviation signals when the aircraft descends below **200** feet in altitude.
- 20 13. The flight control system of claim 7, wherein the flight control module is further configured to select one glideslope deviation from among the first and second glideslope deviations when aircraft altitude is above the predetermined threshold.
14. The flight control system of claim 7, wherein the flight control module further comprises a complementary filter configured to filter a selected glideslope deviation signal based on inertial data including a vertical acceleration and a vertical velocity.

15. The flight control system of claim 7, wherein the flight control module is further configured to translate the inertial glideslope deviation to a guidance control point (GCP) for the aircraft.

5 16. A method of detecting a glideslope deviation for an aircraft during landing, the method comprising:

receiving first and second instrument landing system (ILS) glideslope signals;

10 computing first and second multi-mode receiver (MMR) glideslope deviations with respect to a main landing gear of the aircraft based on the ILS glideslope signals;

filtering the first and second MMR glideslope deviations;

translating a filtered MMR glideslope deviation from the main landing gear to a guidance control point (GCP) for the aircraft;

15 initializing an inertial glideslope deviation computation based on the filtered MMR glideslope deviation when an altitude of the aircraft falls below a predetermined threshold;

integrating inertial data, generated by an inertial reference unit (IRU) for the aircraft, from the filtered MMR glideslope deviation to generate an inertial glideslope deviation with respect to the IRU; and

20 translating the inertial glideslope deviation from the IRU to the GCP.

17. The method of claim 16, wherein filtering the MMR glideslope deviations comprises blending a vertical acceleration and a vertical velocity, both measured by the IRU, with the MMR glideslope deviations using a complementary filter.

18. The method of claim 16, wherein integrating the inertial data generated by the IRU comprises:

5 computing inertial glideslope error based on ground speed and vertical velocity measured by the IRU, and an average glideslope angle computed based on the ground speed and the vertical velocity; and

integrating the inertial glideslope error from the filtered MMR glideslope deviation to generate the inertial glideslope deviation with respect to the IRU.

19. The method of claim 16, wherein translating the filtered MMR glideslope deviation from the main landing gear to the GCP for the aircraft further comprises:

10 computing a vertical position difference between the main landing gear and the GCP based on a pitch attitude measured by the IRU; and

15 applying the vertical position difference to the filtered MMR glideslope deviation.

20. The method of claim 16, wherein translating the inertial glideslope deviation at the IRU to the GCP comprises:

20 computing a vertical position difference between the IRU and the GCP based on a pitch attitude measured by the IRU; and

adding the vertical position difference to the inertial glideslope deviation with respect to the IRU to generate an inertial glideslope deviation with respect to the GCP.

21. A flight control module for computing glideslope deviation during landing of an aircraft, comprising:

a communication interface configured to receive:

inertial data for the aircraft,

5 first and second multi-mode receiver (MMR) glideslope deviation signals indicative of respective glideslope deviations computed based on a glideslope transmission received by the aircraft, and

an altitude of the aircraft measured by an radar altimeter;

10 a processor coupled to the communication interface and configured to compute an inertial glideslope deviation based on the inertial data and a filtered MMR glideslope deviation when the altitude falls below a predetermined threshold, and

15 a signal selection fault detection (SSFD) module configured to select, when the altitude is below the predetermined threshold, one glideslope deviation from among the respective glideslope deviations and the inertial glideslope deviation for use in controlling an automated landing system of the aircraft.

22. The flight control module of claim 21, wherein the SSFD module comprises a mid-value selector configured to select a middle value from among the respective glideslope deviations and the inertial glideslope deviation.

20 23. The flight control module of claim 21 or 22, wherein the processor comprises a complementary filter configured to generate a filtered glideslope deviation based on a glideslope deviation signal received through the communication interface and the inertial data, including a vertical acceleration and a vertical velocity.

25 24. The flight control module of claim 23, wherein the communication interface is configured to be coupled to an inertial reference unit (IRU) through a

communication bus, the IRU comprising a ground speed sensor, a pitch sensor, a vertical velocity sensor, and a vertical acceleration sensor, and wherein the inertial data includes a ground speed, a pitch angle, the vertical velocity, and the vertical acceleration.

5 **25.** The flight control module of claim **24**, wherein the communication interface is further coupled to a radar altimeter configured to measure the altitude of the aircraft and transmit an altitude signal indicative of the altitude onto the communication bus.

10 **26.** The flight control module of claim **25**, wherein the processor is further configured to:

compute an inertial glideslope error with respect to the IRU based on the ground speed, the vertical velocity, and an average glideslope angle computed based on the ground speed and the vertical velocity; and

15 apply a correction to the inertial glideslope error to generate the inertial glideslope deviation, the correction computed based on the pitch attitude and a distance between the IRU and a guidance control point of the aircraft.

20 **27.** A method of detecting a glideslope deviation for an aircraft during landing, the aircraft receiving first and second instrument landing system, ILS, glideslope signals and computing first and second multi-mode receiver, MMR, glideslope deviation signals with respect to a main landing gear of the aircraft based on the first and second ILS glideslope signals, the method comprising:

receiving inertial data for the aircraft;

receiving the first and second MMR glideslope deviation signals indicative of respective glideslope deviations

filtering the first and second MMR glideslope deviations to obtain a filtered MMR glideslope deviation;

translating the filtered MMR glideslope deviation from the main landing gear to a guidance control point (GCP) for the aircraft;

5 initializing an inertial glideslope deviation computation based on the filtered MMR glideslope deviation when an altitude of the aircraft falls below a predetermined threshold;

10 integrating the inertial data, generated by an inertial reference unit (IRU) for the aircraft, from the filtered MMR glideslope deviation to generate an inertial glideslope deviation with respect to the IRU;

translating the inertial glideslope deviation from the IRU to the GCP; and

selecting one glideslope deviation from among the respective first and second glideslope deviations and the inertial glideslope deviation for use in controlling an automated landing system of the aircraft.

15 **28.** The method of claim **27**, wherein filtering the MMR glideslope deviations comprises blending a vertical acceleration and a vertical velocity, both measured by the IRU, with the MMR glideslope deviations using a complementary filter.

29. The method of claim **27** or **28**, wherein integrating the inertial data generated by the IRU comprises:

20 computing inertial glideslope error based on ground speed and vertical velocity measured by the IRU, and an average glideslope angle computed based on the ground speed and the vertical velocity; and

25 integrating the inertial glideslope error from the filtered MMR glideslope deviation to generate the inertial glideslope deviation with respect to the IRU.

30. The method of any one of claims **27-29**, wherein translating the filtered MMR glideslope deviation from the main landing gear to the GCP for the aircraft further comprises:

5 computing a vertical position difference between the main landing gear and the GCP based on a pitch attitude measured by the IRU; and

 applying the vertical position difference to the filtered MMR glideslope deviation.

31. The method of any one of claims **27-30**, wherein translating the inertial glideslope deviation at the IRU to the GCP comprises:

10 computing a vertical position difference between the IRU and the GCP based on a pitch attitude measured by the IRU; and

 adding the vertical position difference to the inertial glideslope deviation with respect to the IRU to generate an inertial glideslope deviation with respect to the GCP.

15 32. The method of any one of claims **27-31**, wherein the initializing the inertial glideslope deviation computation comprises latching the filtered MMR glideslope deviation upon an altitude of the aircraft falling below a predetermined threshold.

20 33. The method of any one of claims **27-32** wherein a middle value is selected by a mid-value selector, from among the respective glideslope deviations and the inertial glideslope deviation.

34. The method of claim **33**, wherein the IRU comprises a ground speed sensor, a pitch sensor, a vertical velocity sensor, and a vertical acceleration sensor, and wherein the inertial data includes a ground speed, a pitch angle, the velocity and the vertical acceleration.

25

35. The method of claim **34**, wherein the altitude signal is transmitted indicative of the altitude.

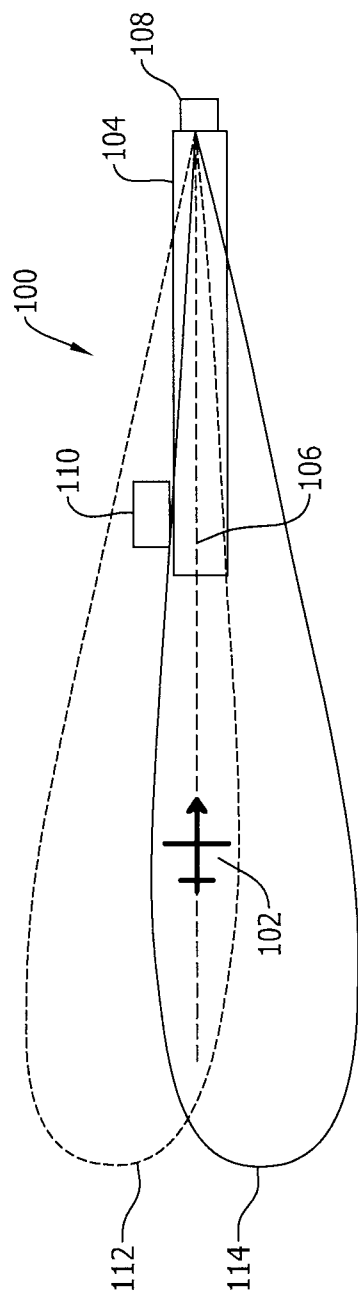


FIG. 1

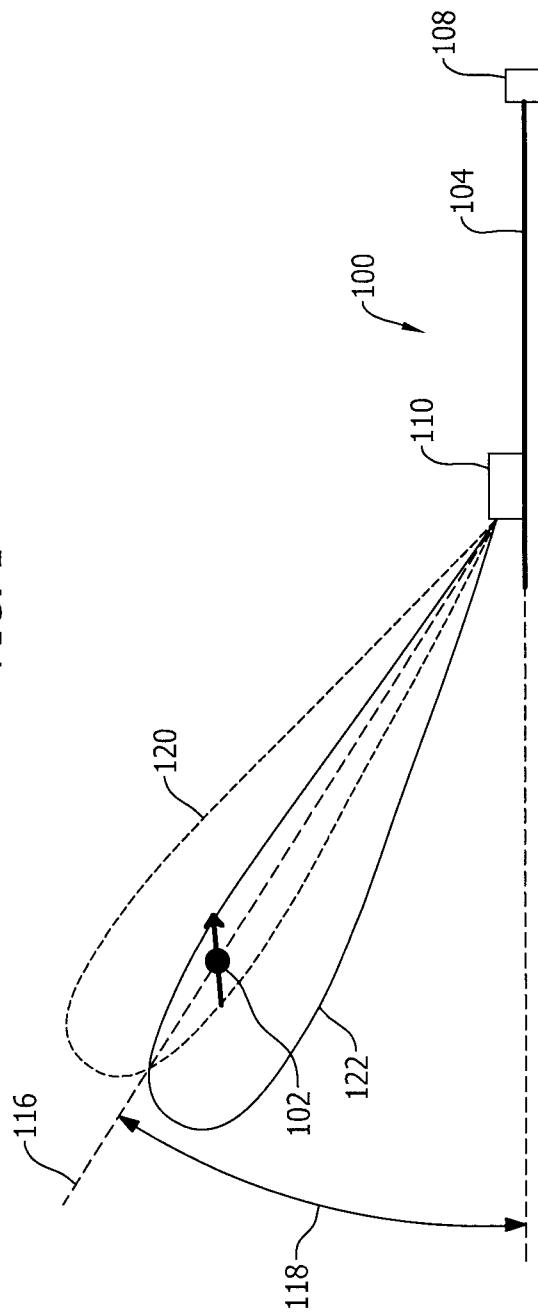


FIG. 2

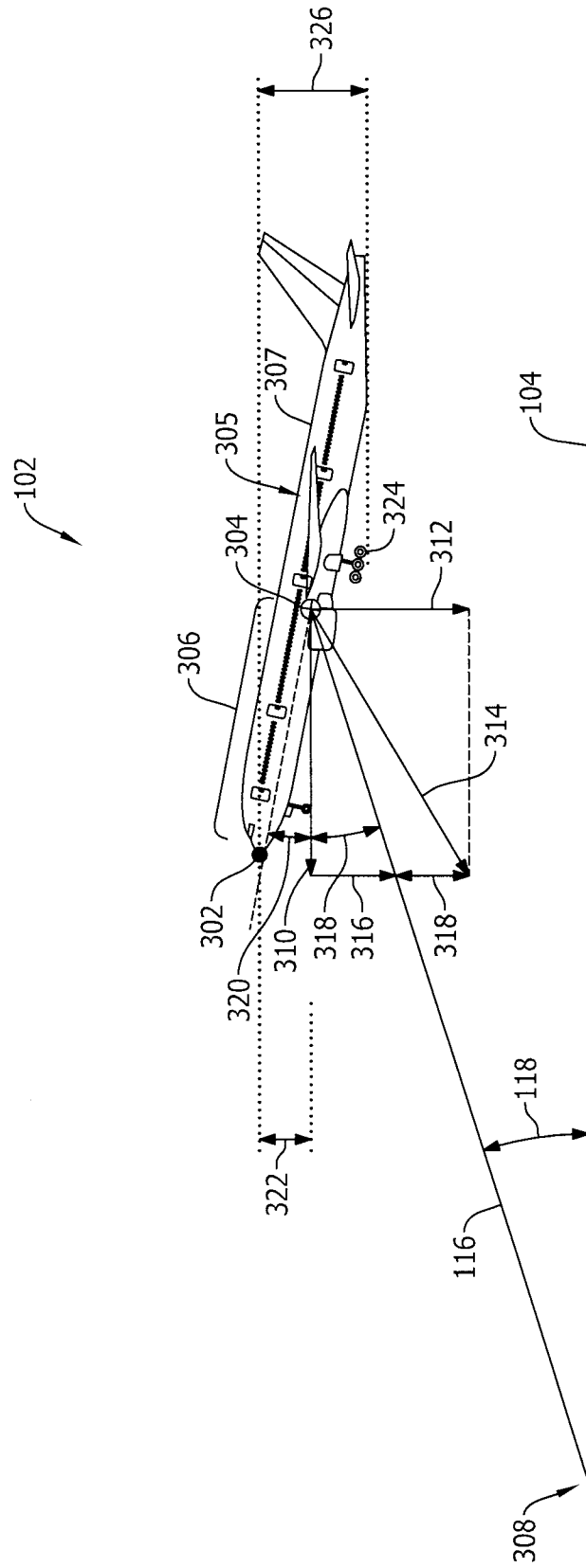


FIG. 3

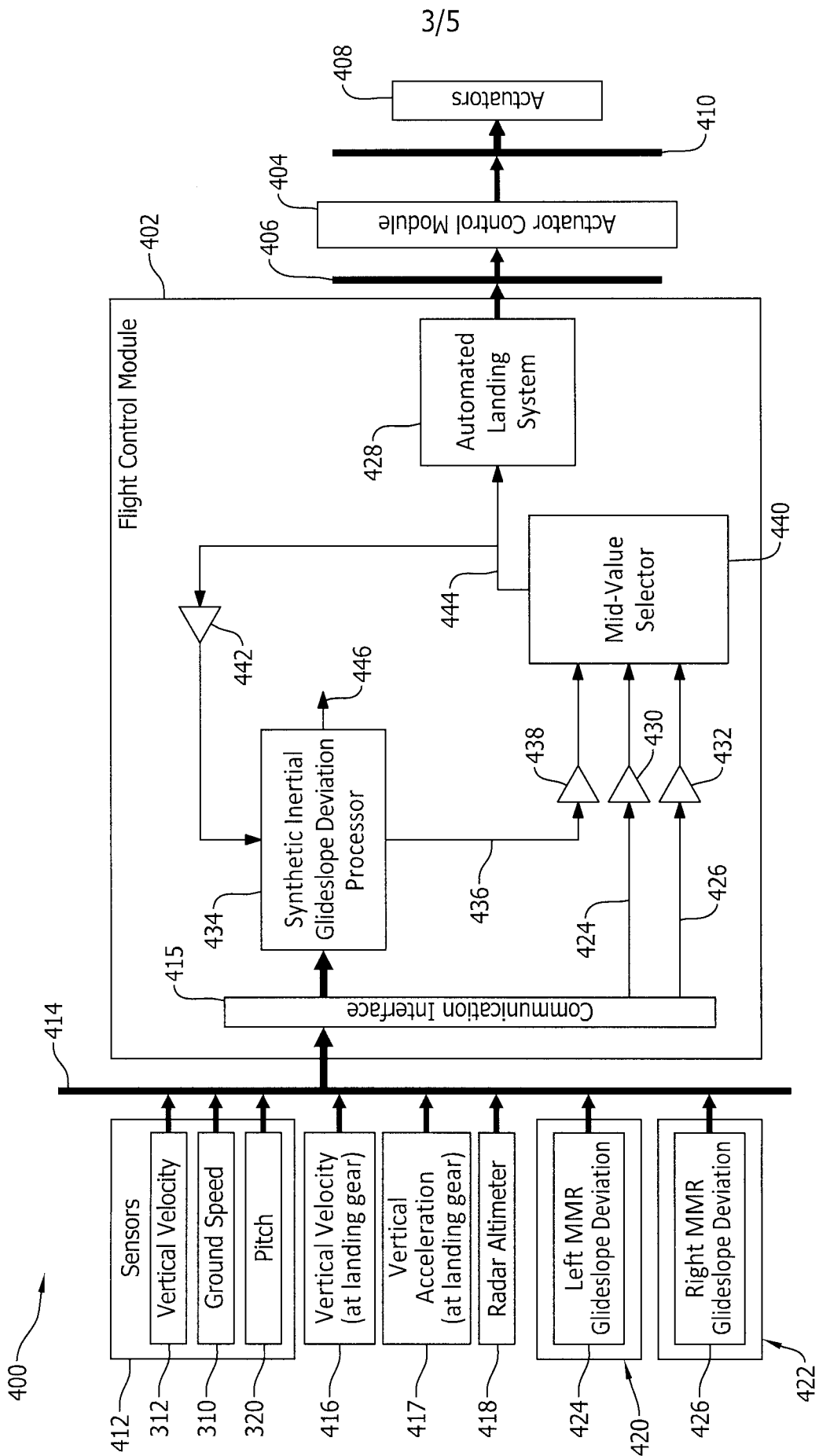


FIG. 4

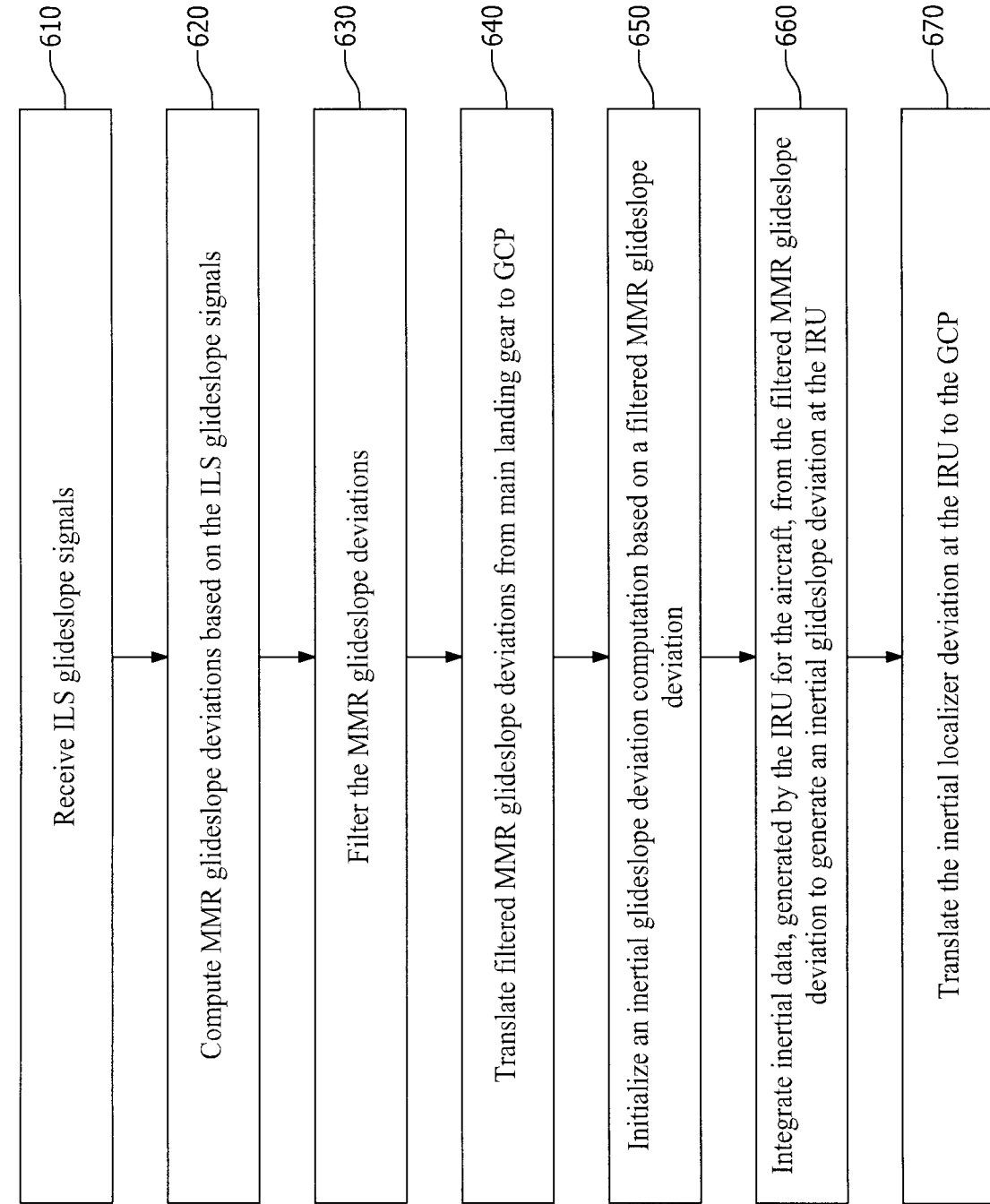


FIG. 6

