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(54) **REAL-TIME VISUAL-INERTIAL MOTION TRACKING FAULT DETECTION**

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G06T 7/73	(2006.01)

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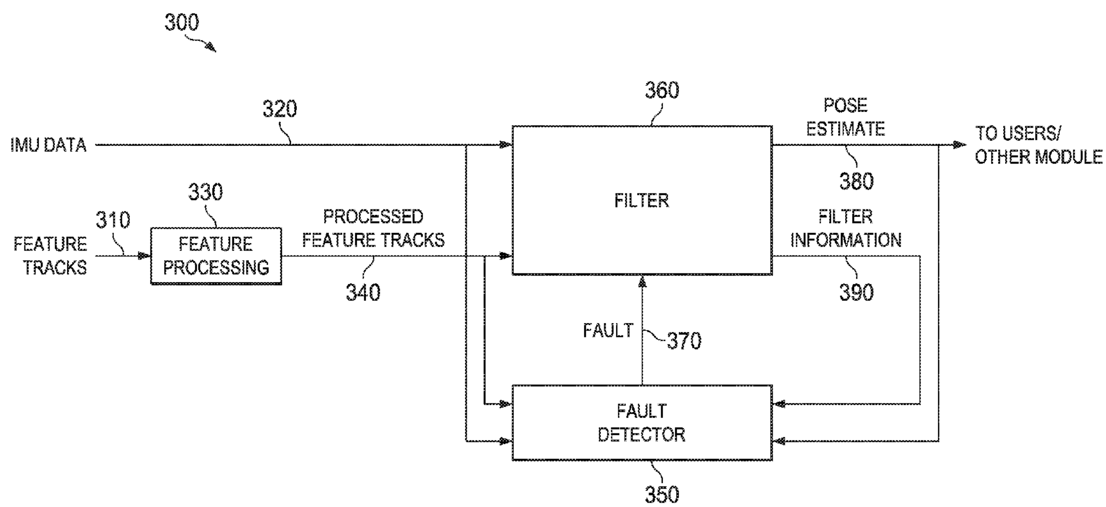
(57) **ABSTRACT**

Fault detection for real-time visual-inertial odometry motion tracking. A fault detection system allows immediate detection of error when the motion of a device cannot be accurately determined. The system includes subdetectors that operate independently and in parallel to a main system on a device to determine if a condition exists which results in a main system error. Each subdetector covers a phase of a six-degrees of freedom (6DOF) estimation. If any of the subdetectors detect an error, a fault is output to the main system to indicate a motion tracking failure.



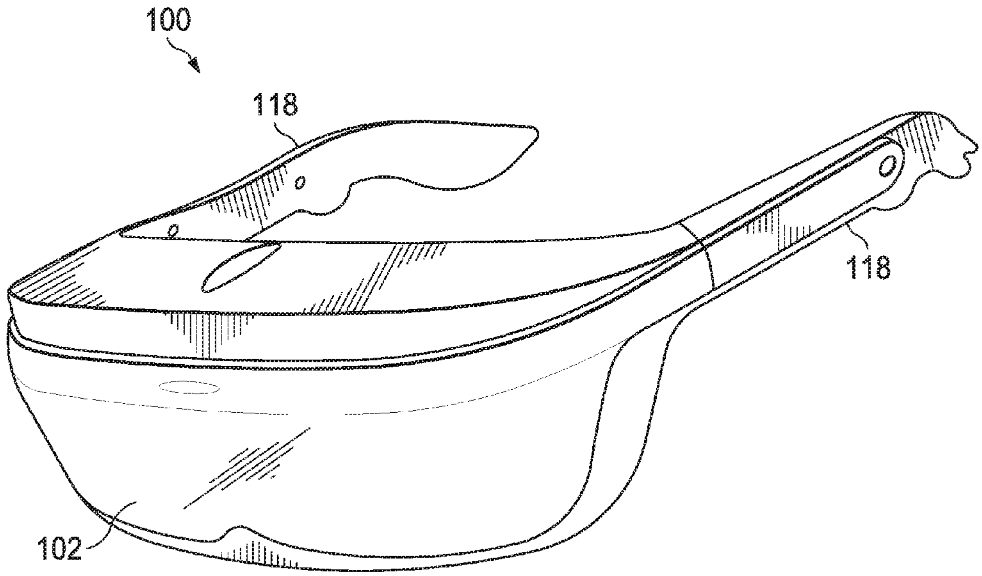


FIG. 1A

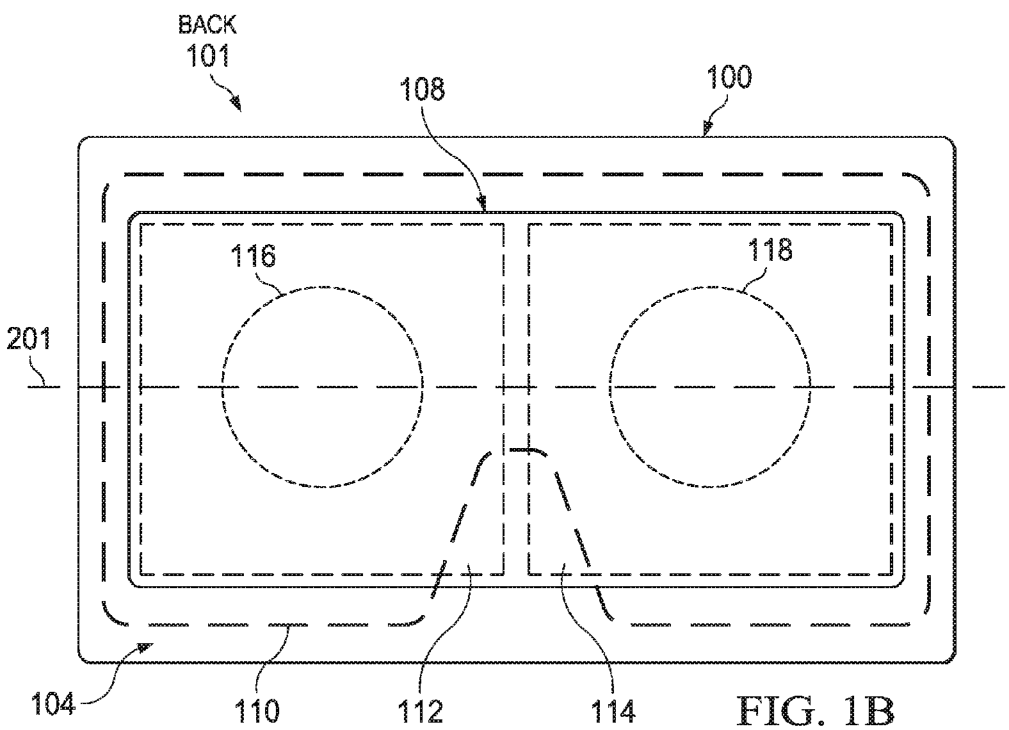
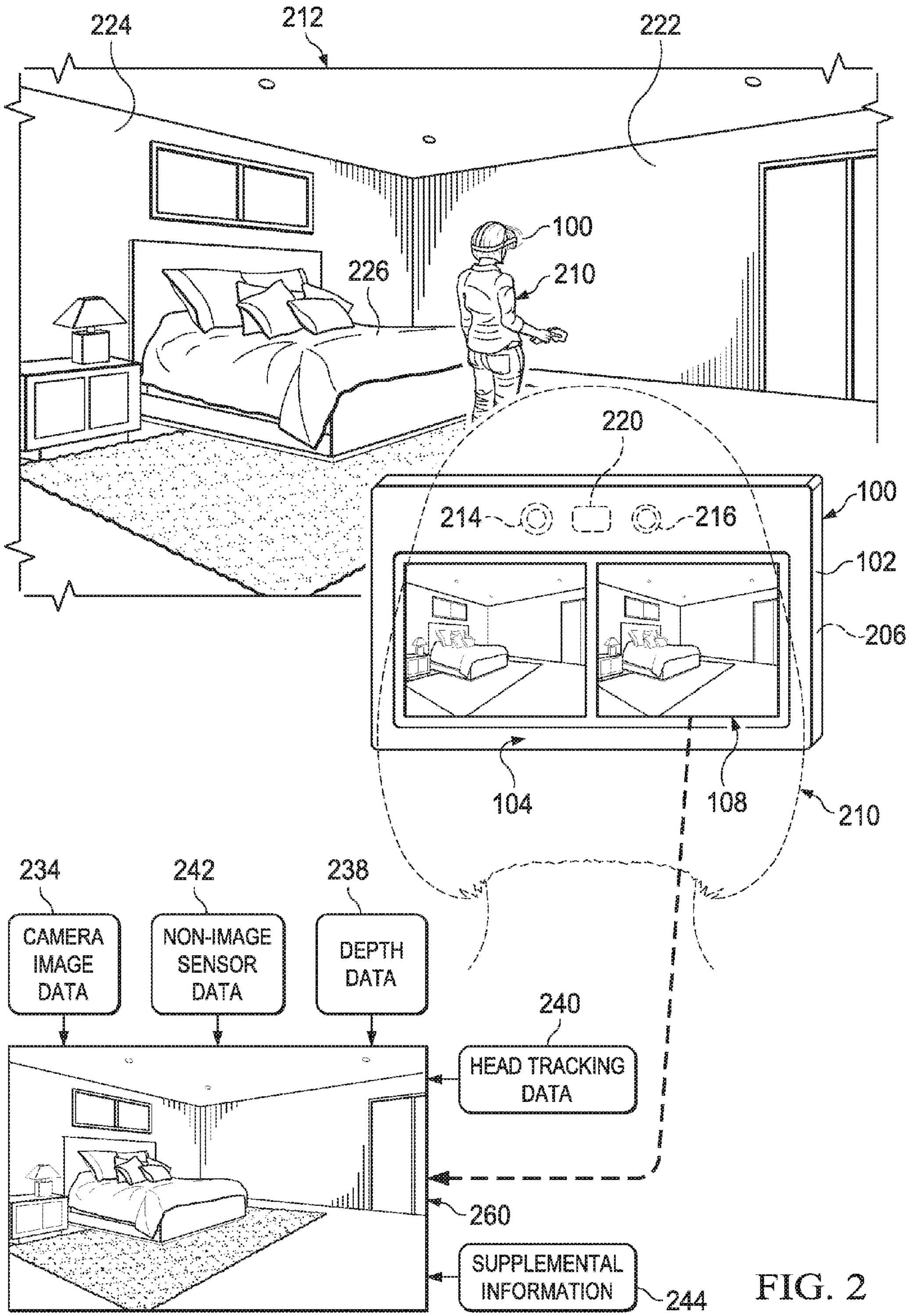


FIG. 1B



224
212
222
100
210
226
220
100
214
216
102
206
104
108
210
234
242
238
CAMERA IMAGE DATA
NON-IMAGE SENSOR DATA
DEPTH DATA
240
HEAD TRACKING DATA
260
SUPPLEMENTAL INFORMATION
244

FIG. 2

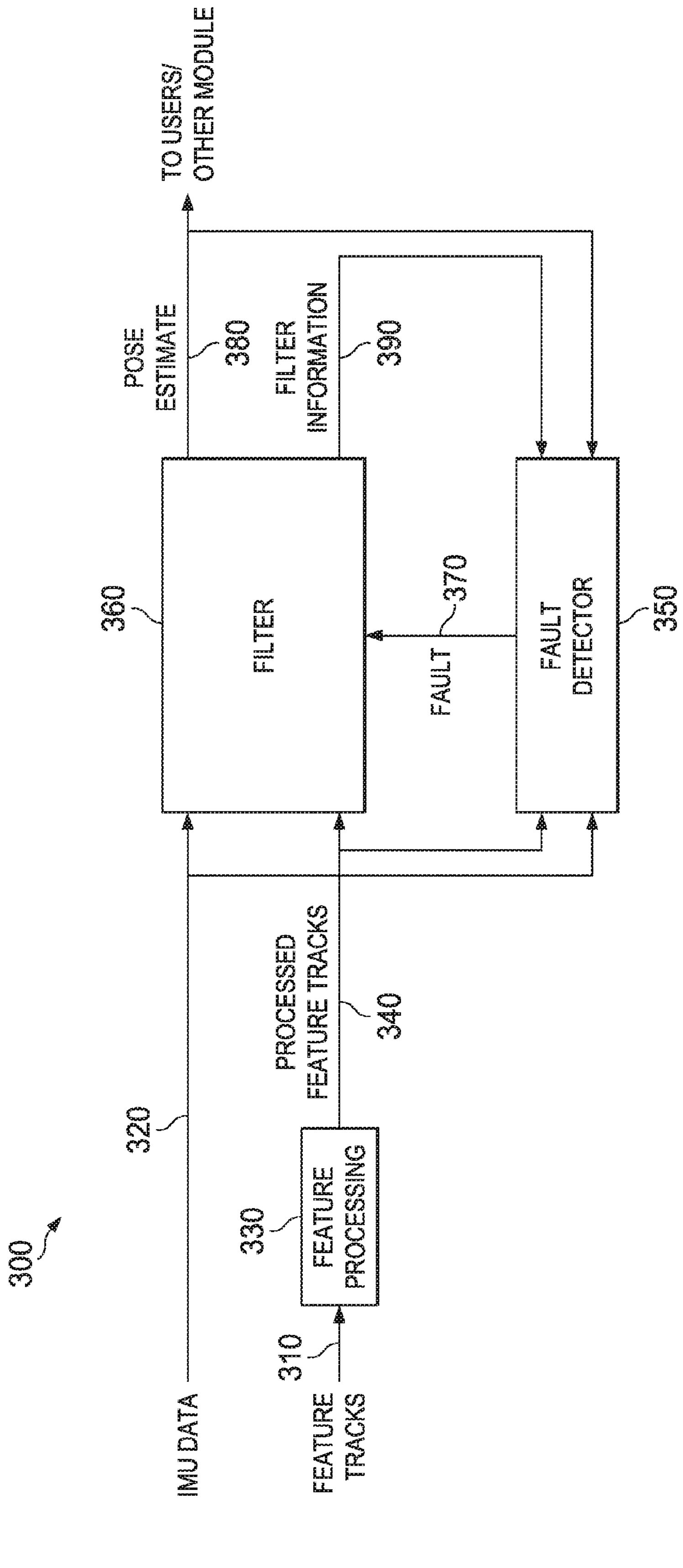

300
IMU DATA
320
FEATURE TRACKS
310
FEATURE PROCESSING
330
PROCESSED FEATURE TRACKS
340
FILTER
360
FAULT
370
FAULT DETECTOR
350
POSE ESTIMATE
380
FILTER INFORMATION
390
TO USERS/ OTHER MODULE

FIG. 3

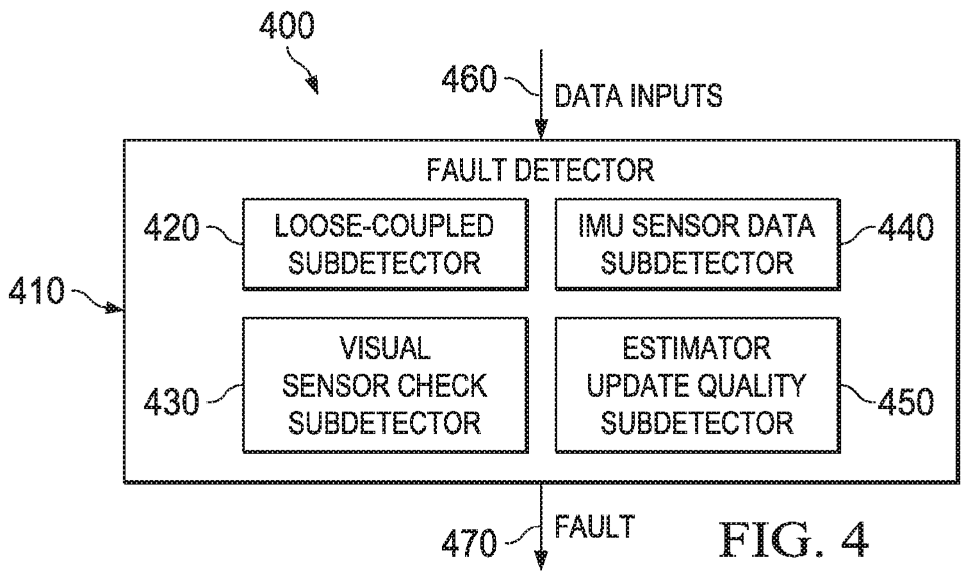

400
460
DATA INPUTS
FAULT DETECTOR
420
LOOSE-COUPLED SUBDETECTOR
IMU SENSOR DATA SUBDETECTOR
440
410
430
VISUAL SENSOR CHECK SUBDETECTOR
ESTIMATOR UPDATE QUALITY SUBDETECTOR
450
470
FAULT

FIG. 4

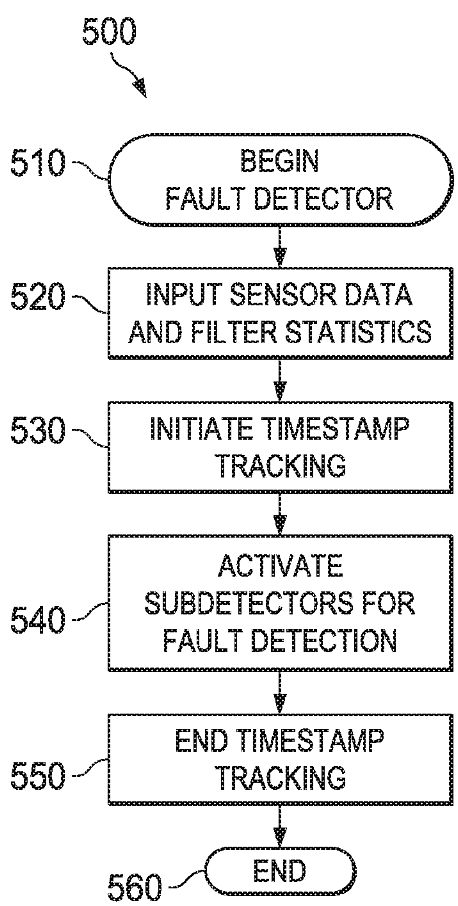

500
510
BEGIN FAULT DETECTOR
520
INPUT SENSOR DATA AND FILTER STATISTICS
530
INITIATE TIMESTAMP TRACKING
540
ACTIVATE SUBDETECTORS FOR FAULT DETECTION
550
END TIMESTAMP TRACKING
560
END

FIG. 5

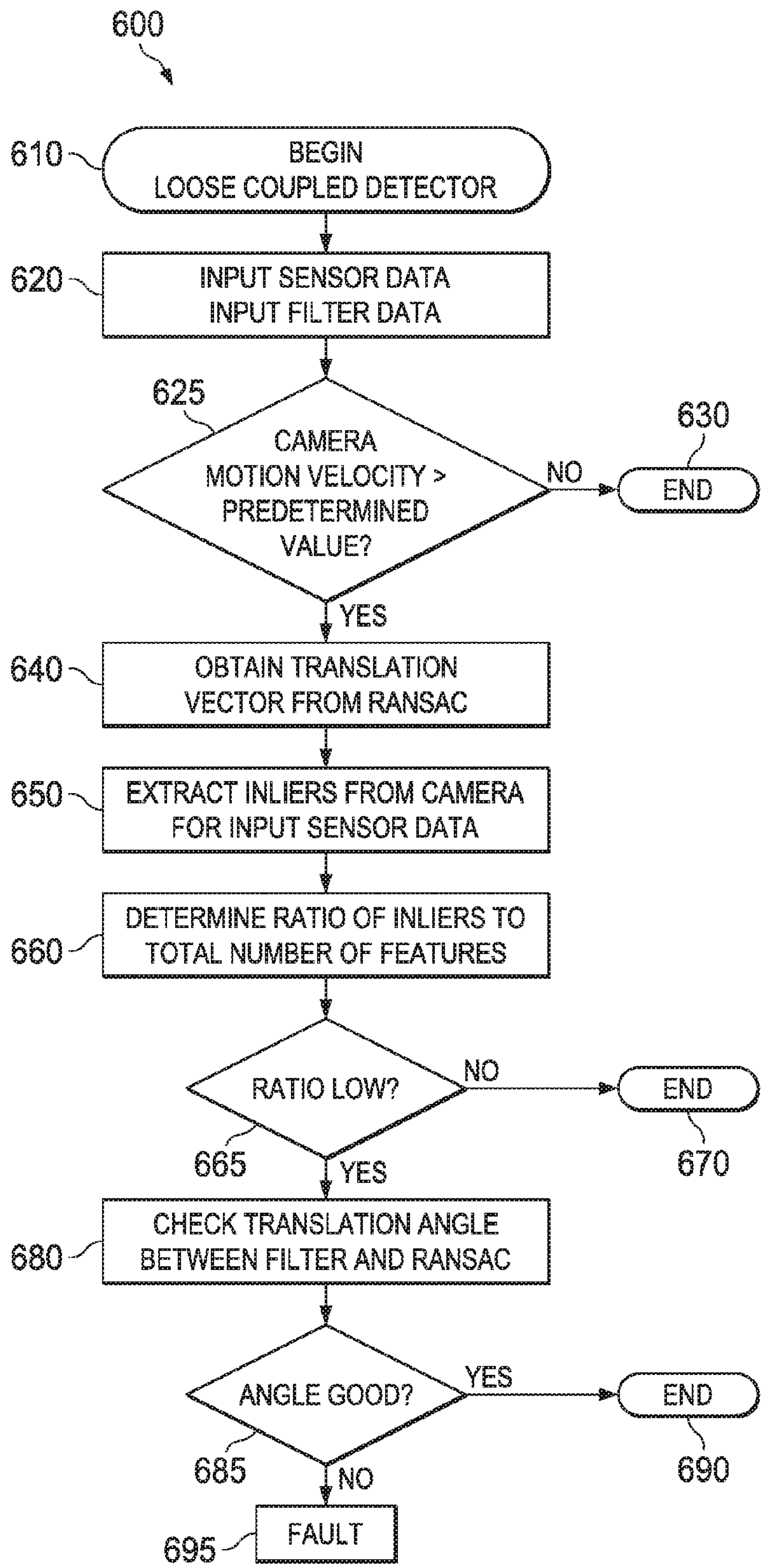

600
610
BEGIN
LOOSE COUPLED DETECTOR
620
INPUT SENSOR DATA
INPUT FILTER DATA
625
CAMERA
MOTION VELOCITY >
PREDETERMINED
VALUE?
NO
630
END
YES
640
OBTAIN TRANSLATION
VECTOR FROM RANSAC
650
EXTRACT INLIERS FROM CAMERA
FOR INPUT SENSOR DATA
660
DETERMINE RATIO OF INLIERS TO
TOTAL NUMBER OF FEATURES
RATIO LOW?
NO
END
670
665
YES
680
CHECK TRANSLATION ANGLE
BETWEEN FILTER AND RANSAC
ANGLE GOOD?
YES
END
690
685
NO
695
FAULT

FIG. 6

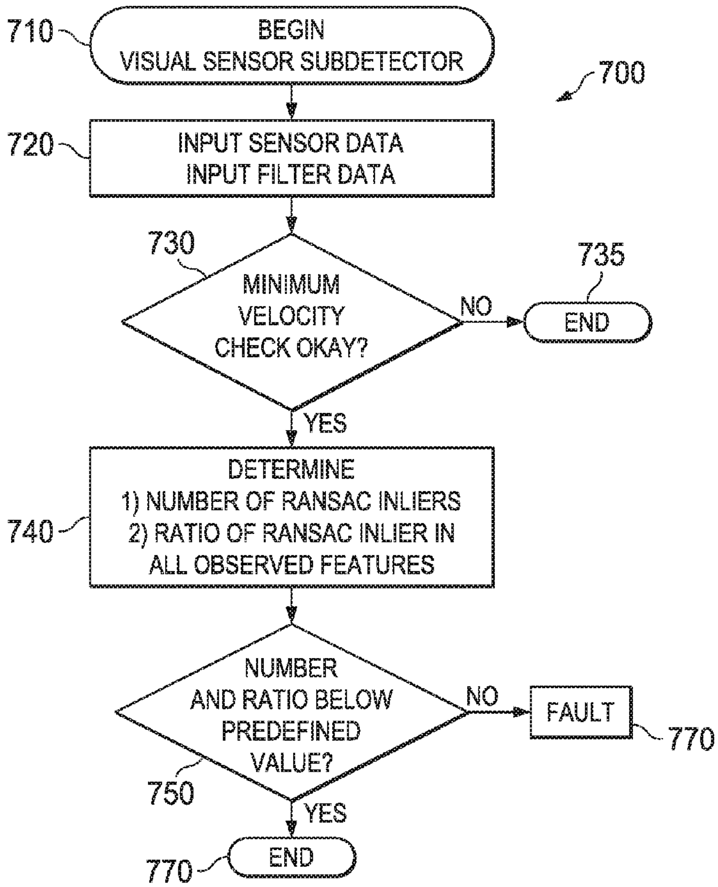

710
BEGIN
VISUAL SENSOR SUBDETECTOR
700
720
INPUT SENSOR DATA
INPUT FILTER DATA
730
MINIMUM
VELOCITY
CHECK OKAY?
NO
735
END
YES
DETERMINE
1) NUMBER OF RANSAC INLIERS
2) RATIO OF RANSAC INLIER IN
ALL OBSERVED FEATURES
740
NUMBER
AND RATIO BELOW
PREDEFINED
VALUE?
NO
FAULT
770
750
YES
770
END

FIG. 7

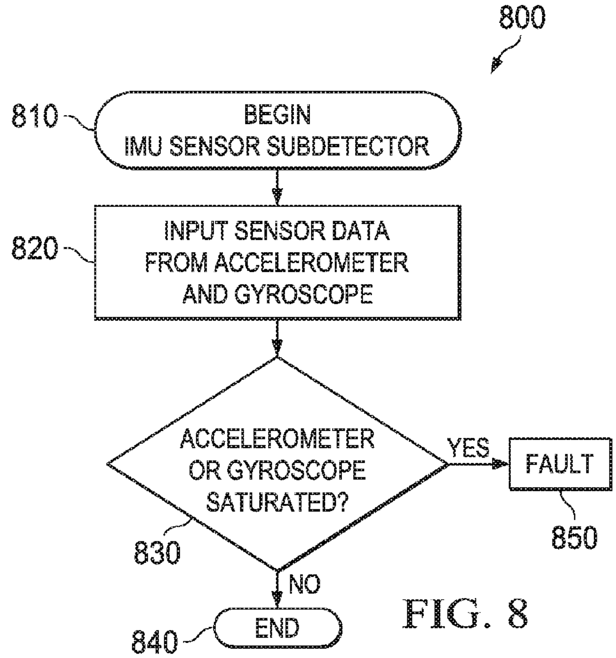

800
810
BEGIN
IMU SENSOR SUBDETECTOR
820
INPUT SENSOR DATA
FROM ACCELEROMETER
AND GYROSCOPE
ACCELEROMETER
OR GYROSCOPE
SATURATED?
YES
FAULT
830
850
NO
840
END

FIG. 8

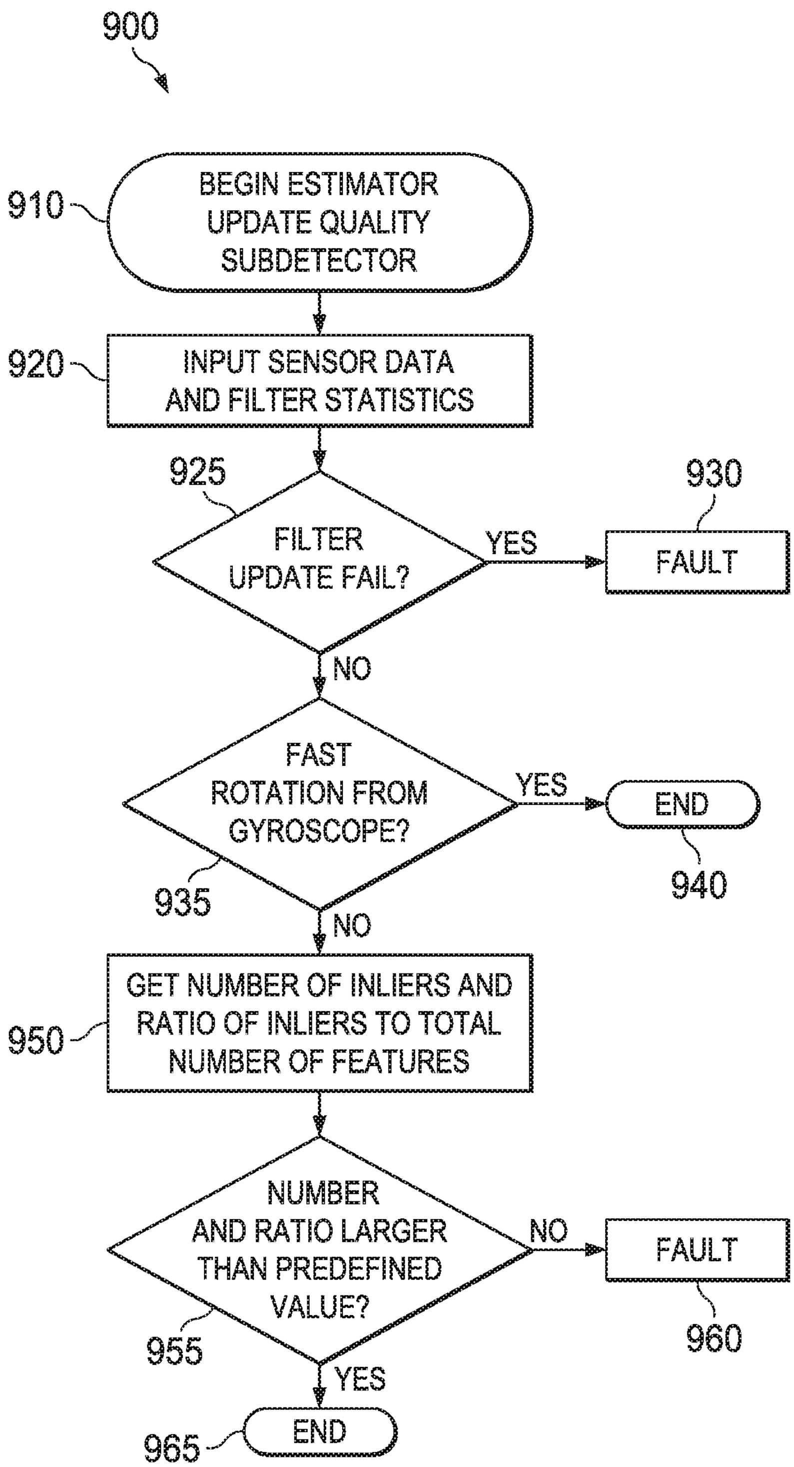

900
910
BEGIN ESTIMATOR UPDATE QUALITY SUBDETECTOR
920
INPUT SENSOR DATA AND FILTER STATISTICS
925
FILTER UPDATE FAIL?
YES
930
FAULT
NO
FAST ROTATION FROM GYROSCOPE?
YES
END
940
935
NO
950
GET NUMBER OF INLIERS AND RATIO OF INLIERS TO TOTAL NUMBER OF FEATURES
NUMBER AND RATIO LARGER THAN PREDEFINED VALUE?
NO
FAULT
960
955
YES
965
END

FIG. 9

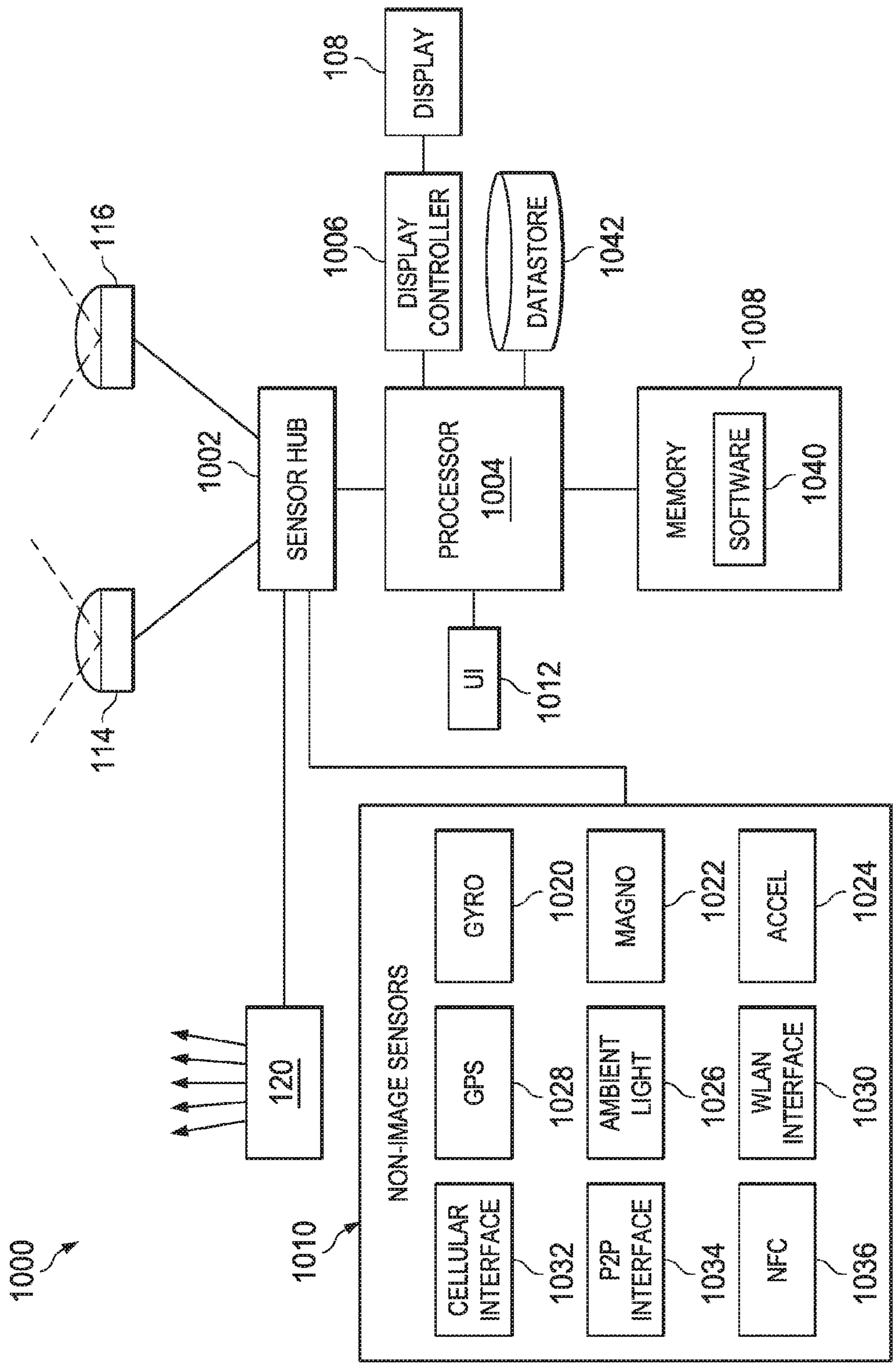

1000
116
114
1002
SENSOR HUB
108
DISPLAY
1006
DISPLAY CONTROLLER
DATASTORE
1042
PROCESSOR
1004
1008
MEMORY
SOFTWARE
1040
UI
1012
120
1010
NON-IMAGE SENSORS
GYRO
1020
MAGNO
1022
ACCEL
1024
GPS
1028
AMBIENT LIGHT
1026
WLAN INTERFACE
1030
CELLULAR INTERFACE
1032
P2P INTERFACE
1034
NFC
1036

FIG. 10

REAL-TIME VISUAL-INERTIAL MOTION TRACKING FAULT DETECTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Patent Application Ser. No. 62/337,987 (Attorney Docket No. 1500-G16013-PR), entitled "Methods And Systems For VR/AR Functionality In A Portable Device" and filed on 18 May 2016, the entirety of which is incorporated by reference herein for all purposes.

BACKGROUND

Field of the Disclosure

[0002] The present disclosure relates generally to motion tracking and a system for detecting and recovering from faults during motion tracking.

Description of the Related Art

[0003] Motion tracking allows a device to understand its motion with respect to position and orientation as it moves through an area. Motion tracking is useful in virtual reality applications such as gaming which allows a user to explore a virtual world from a fixed viewpoint. The tracked motion can be characterized by how many degrees of freedom are possible in movement, for example, either three degrees of freedom (3DoF) or six degrees of freedom (6DoF). In virtual reality applications, tracking motion with respect to 6DoF can provide an improved user experience because the tracking captures rotational movement and translational movement in the X, Y, and Z directions.

[0004] A device may employ visual-inertial odometry to track motion. Visual-inertial odometry enables the device to estimate, in real-time, its position and orientation, referred to as a pose. If a device is unable to identify its pose, the quality of the user experience is reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] For a better understanding of the disclosure and the various embodiments described herein, reference is now made to the following brief description, taken in connection with the accompanying drawings and detailed description, which show at least one exemplary embodiment.

[0006] FIG. **1** consisting of FIG. **1**A and FIG. **1**B illustrates HMDs in accordance with an illustrative embodiment of the disclosure;

[0007] FIG. **2** illustrates a block diagram of a HMD system and environment in accordance with an illustrative embodiment of the disclosure;

[0008] FIG. **3** illustrates an exemplary fault detection system in accordance with an illustrative embodiment of the disclosure;

[0009] FIG. **4** illustrates a block diagram of a fault detection module in accordance with an illustrative embodiment of the disclosure;

[0010] FIG. **5** illustrates a flowchart of a method of fault detection in accordance with an illustrative embodiment of the disclosure;

[0011] FIG. **6** illustrates a flowchart of a method of operation of the loose-coupled subdetector of FIG. **4** in accordance with an illustrative embodiment of the disclosure;

[0012] FIG. **7** illustrates a flowchart of a method of operation of the visual sensor check subdetector of FIG. **4** in accordance with an illustrative embodiment of the disclosure;

[0013] FIG. **8** illustrates a flowchart of the method of the IMU sensor data sub-detector of FIG. **4** in accordance with an illustrative embodiment of the disclosure;

[0014] FIG. **9** illustrates a flowchart of the method of the estimator update quality subdetector of FIG. **4** in accordance with an illustrative embodiment of the disclosure; and

[0015] FIG. **10** illustrates a block diagram of a processing system in which a fault detection system may be implemented in accordance with an illustrative embodiment of the disclosure.

DETAILED DESCRIPTION

[0016] It should be understood at the outset that although an illustrative implementation of one or more embodiments are provided below, the description is not to be considered as limiting the scope of the embodiments described herein. The disclosure may be implemented using any number of technique, whether currently known or in existence. The disclosure should in no way be limited to the illustrative implementations, drawings, and techniques illustrated and described herein, which may be modified within the scope of the appended claims along with a full scope of equivalence.

[0017] The present disclosure provides a fault detection system to detect fault conditions when a visual-inertial odometry (VIO) estimator of an electronic device is unable to accurately estimate the motion of the device. The fault detection system includes a plurality of subdetectors that independently operate to detect different failure conditions in a motion tracking system. If any of these subdetectors detect a failure, a motion tracking failure message or fault is triggered by the fault detection system. A number of factors may trigger a fault. For example, in one embodiment, a fault may be caused by the electronic device moving such that the images it captures becomes blurred such as in cases where the electronic device may be shaken or tossed about rapidly. In another embodiment, a fault may be triggered by the inertial measurements from an accelerometer or gyroscope becoming saturated. Saturation is a state in which the signals that needs to be measured is larger than the dynamic range of the sensor. In some embodiments, a fault that is triggered by the subdetectors may result in a fault detection system reset.

[0018] Referring first to FIG. **1**, illustrative embodiments of electronic devices in which the fault detection system may be implemented is shown. Electronic devices can include a portable user device, such as head mounted display (HMD), a tablet computer, computing-enabled cellular phone (e.g., a "smartphone"), a notebook computer, a personal digital assistant (PDA), a gaming console system, and the like. In other embodiments, the electronic device can include a fixture device, such as medical imaging equipment, a security imaging sensor system, an industrial robot control system, a drone control system, and the like. For ease of illustration, the electronic device **100** is generally described herein in the example context of an HMD system. However, the electronic device is not limited to these example implementations.

[0019] FIG. **1**A illustrates an electronic device in a HMD **100** form factor in accordance with an illustrative embodiment of the disclosure. The HMD **100** may be implemented in other form factors, such as a smart phone form factor, tablet form factor and the like, which implement configurations analogous to those illustrated. HMD **100** has a housing **102** that is mounted on the head of a user by a set of straps **118** or harness. HMD **100** is meant to immerse the user in whatever image is being displayed on the device.

[0020] FIG. **1**B illustrates a back plan view **101** of an illustrative embodiment of the electronic device **100** of FIG. **1**A in accordance with at least one embodiment of the present disclosure. As illustrated by the back plan view **100** of FIG. **1**B, the HMD **100** can include the display device **108** disposed at the surface **104**, a face gasket **110** for securing the electronic device **100** to the face of a user (along with the use of straps or a harness), and eyepiece lenses **116** and **118**, one each for the left and right eyes of the user **110**. As depicted in the back plan view **101**, the eyepiece lens **116** is aligned with a left-side region **112** of the display area of the display device **108**, while the eyepiece lens **118** is aligned with a right-side region **114** of the display area of the display device **108**. Thus, in a stereoscopic display mode, imagery captured by an imaging sensor (not shown) may be displayed in the left-side region **112** and viewed by the user's left eye via the eyepiece lens **116** and imagery captured by the imaging sensor may be displayed in the right-side region **114** and viewed by the user's right eye via the eyepiece lens **118**.

[0021] FIG. **2** illustrates a detailed view of a HMD system and environment **200**. In FIG. **2**, HMD **100** includes a housing **102** having a surface **104** opposite another surface **206**, as well as a set of straps or a harness (not shown) to mount the housing **102** on the head of a user **210** so that the user faces the surface **104** of the housing **102**. In the illustrative thin rectangular block form-factor depicted, the surfaces **104** and **206** are substantially parallel with the housing **102**. The housing **102** may be implemented in many other form factors, and the surfaces **104** and **206** may have a non-parallel orientation. For the illustrated HMD system implementation, the HMD **100** includes a display device **108** disposed at the surface **206** for presenting visual information to the user **210**.

[0022] For ease of reference, the surface **206** is referred to herein as the "forward-facing" surface and the surface **104** is referred to herein as the "user-facing" surface as a reflection of this example orientation of the electronic device **100** relative to the user **210**, although the orientation of these surfaces is not limited by these relational designations.

[0023] HMD **100** includes a plurality of sensors to obtain information regarding a local environment **212**, or "space", of the HMD **100**. The HMD **100** obtains visual information (imagery) for the local environment **212** via one or more imaging sensors, such as imaging sensors **214**, **216**, disposed at the forward-facing surface **206**. In one embodiment, the imaging sensor **214** is implemented as a wide-angle imaging sensor having a fish-eye lens or other wide-angle lens to provide a wider angle view of the local environment **212** facing the surface **206**, while the imaging sensor **216** is implemented as a narrow-angle imaging sensor having a typical angle of view lens to provide a narrower angle view of the local environment **212** facing the surface **206**. Accordingly, the imaging sensor **214** and the imaging sensor **216** are also referred to herein as the "wide-angle imaging sensor **214**" and the "narrow-angle imaging sensor **216**," respectively. In one embodiment, the HMD **100** may use a wide-angle lens of up to 260 degrees to enable capture of the details of the environment to improve feature tracking. A feature track is generated by identifying one or more image features in a first image frame and then matching those one or more image features with one or more corresponding image features in consecutive frames. By matching image features over successive pairs of image frames, a list of feature tracks may be formed with each feature track containing a sequence of image feature locations across the frames.

[0024] One or more of the imaging sensors **214**, **216** may serve other imaging functions for the HMD **100** in addition to capturing imagery of the local environment **212**. To illustrate, the imaging sensors **214**, **216** may be used to support visual telemetry functionality, such as capturing imagery to support position and orientation detection. Further, in some embodiments, an imaging sensor (not shown) disposed at the user-facing surface **104** may be employed for tracking the movements of the head of the user **210** or for facial recognition, and thus providing head tracking information that may be used to adjust a view perspective of imagery presented via the display device **108**. The HMD **100** also may rely on non-image information for pose detection. This non-image information can be obtained by the HMD **100** via one or more non-image sensors (not shown in FIG. **1**), such as a gyroscope or ambient light sensor. The non-image sensors also can include user interface components, such as a keypad (e.g., touchscreen or keyboard), microphone, mouse, and the like.

[0025] In operation, the HMD **100** captures imagery of the local environment **212** via one or both of the imaging sensors **214**, **216**, modifies or otherwise processes the captured imagery, and provides the processed captured imagery for display on the display device **108**. In implementations with two imaging sensors, the imagery from the left side imaging sensor **214** may be processed and displayed in left side region of the display device **108** concurrent with the processing and display of the imagery from the right side imaging sensor **216** in a right side region of the display device **108**, thereby enabling a stereoscopic 3D display of the captured imagery.

[0026] In addition to capturing imagery of the local environment **212** for display with augmented reality (AR) or virtual reality (VR) modification, in at least one embodiment the HMD **100** uses the image sensor data and the non-image sensor data to determine a relative pose (that is, position and/or orientation) of the HMD **100**, that is, a pose relative to the local environment **212**. This relative pose information may be used by the HMD **100** in support of simultaneous location and mapping (SLAM) functionality, visual odometry, or other location-based functionality.

[0027] The determination of the relative pose may be based on the detection of spatial features in image data captured by one or more of the imaging sensors **214**, **216** and the determination of the pose of the HMD **100** relative to the detected spatial features. To illustrate, in the illustrated example of FIG. **2**, the local environment **212** includes a hallway of an office building that includes three corners **224**, **226**, and **128**, a baseboard **130**, and an electrical outlet **132**. The user **210** has positioned and oriented the HMD **100** so that the imaging sensors **214** and **216** capture camera image data **234** that includes these spatial features of the hallway. In this example, the depth sensor **220** also captures depth data **238** that reflects the relative distances of these spatial features relative to the current pose of the HMD **100**.

Further, a user-facing imaging sensor (not shown) captures image data representing head tracking data **240** for the current pose of the head of the user **210**. Non-image sensor data **242**, such as readings from a gyroscope, a magnetometer, an ambient light sensor, a keypad, a microphone, and the like, also is collected by the HMD **100** in its current pose.

[0028] From this input data, the HMD **100** can determine its relative pose without explicit absolute localization information from an external source. To illustrate, the HMD **100** can perform multiview analysis of the wide angle imaging sensor image data **234** and the narrow angle imaging sensor image data **136** to determine the distances between the HMD **100** and the corners **224**, **226**, **128**. Alternatively, the depth data **238** obtained from the depth sensor **220** can be used to determine the distances of the spatial features. From these distances the HMD **100** can triangulate or otherwise infer its relative position in the office represented by the local environment **212**. As another example, the HMD **100** can identify spatial features present in one set of captured image frames of the image data **234**, determine the initial distances to these spatial features, and then track the changes in position and distances of these spatial features in subsequent captured imagery to determine the change in pose of the HMD **100**. In this approach, certain non-image sensor data, such as gyroscopic data or accelerometer data, can be used to correlate spatial features observed in one image frame with spatial features observed in a subsequent image frame.

[0029] A breakdown in motion tracking for HMD **100** may occur during movement such as adjusting a HMD **100** display, mounting a HMD **100** onto the head of a user, head shaking while the device is on, or other aggressive fast movements while the HMD **100** is mounted on the head. A fault detection system of the HMD **100** detects the motion tracking failure and may reset or reinitialize the system, as described further herein.

[0030] Turning now to FIG. **3**, an exemplary fault detection system **300** of the HMD **100** in accordance with an illustrative embodiment of the disclosure is illustrated. In FIG. **3**, filter **360** estimates the relative position of a device or object over time based on input data that provides orientation and direction. In an embodiment, filter **360** is a visual inertial odometry filter. Filter **360** may receive inertial measurement unit (IMU) data **320** from an IMU (not shown) of the HMD **100**. The IMU data **320** indicates real world linear acceleration of movement, orientation and gravitational forces based on devices of the IMU such as, without limitation, accelerometers and gyroscopes, and reports that information is provided to the filter **360**. Filter **360** also receives processed feature tracks **340** that originate from feature track processing **330** of camera images **310**. Filter **360** combines or fuses the IMU data **320** and the processed feature tracks **340** and outputs a position and orientation estimate, pose estimate **380** within 6DoF.

[0031] Fault detector **350** inputs pose estimate **380** and filter information **390** that is the fused IMU data **320** and processed feature tracks **340** in addition to the raw IMU data **320** and processed feature tracks **340**. The pose provides the orientation and position of a device within a motion tracking framework such as 6DoF or 3DoF relative to a local environment. As the filter **360** estimates motion in a 6DoF sphere, fault detector **350** keeps track of the motion and issues a fault upon determining that an error in the pose estimate is occurring. In response to determining the error, the fault detector **350** sends a fault **370** to filter **360**. A fault may occur when the filter **360** is not able to correctly estimate motion. The fault may reset filter **360** to enable a quick reinitialization of the system for continued motion tracking.

[0032] Referring to FIG. **4**, a block diagram of fault detection module in accordance with an illustrative embodiment of the disclosure is illustrated. System **400** operates a fault detector **410** that includes a plurality of detectors that may operate in parallel. In one embodiment, fault detector **410** may include four subdetectors, such as, for example, a loose-coupled subdetector **420**, visual sensor check subdetector **430**, inertial measurement unit (IMU) sensor data subdetector **440** and estimator update quality subdetector **450**. Each of the four subdetectors in fault detector **410** accepts data inputs **460** which may include sensory data or filter statistics. One or more of the four subdetectors in fault detector **410** may be individually triggered based on a unique set of conditions in each respective subdetector to signal a failure condition and output a fault **460** signal based on the failure condition.

[0033] Turning first to loose-coupled subdetector **410**, the subdetector compares the motion detection data from two sources. The first source is filter data which includes real-time motion tracking data such as camera image data and inertial measurement unit (IMU) data. The second source is from an image processing source, such as a random sample consensus or RANSAC algorithm. A RANSAC algorithm may be performed to automatically obtain a direction of translation or motion between two images. The comparison between the results from the RANSAC algorithm and results from the filter seeks to determine whether an angle of consistency exists between the image processing source data and the camera image data. If an angle of consistency is determined not to exist for a threshold period of time (for example, approximately 400 milliseconds), then the loose coupled subdetector **420** issues a fault. Consistency may be determined if the angle of the RANSAC error is within 25 degrees to 35 degrees.

[0034] The visual sensor subdetector **430** checks whether or not the feature tracks from camera data that is input to the fault detector **410** are able to provide stable motion tracking good Features are uniquely identifiable images within images. The features create feature tracks when a same feature corresponds in a sequence of images. Image sequences may be detected by external sensors such as cameras. The IMU sensor data subdetector **440** checks two sensors to determine whether or not saturation has occurred. One sensor may be an accelerometer. The other sensor may be a gyroscope. A sensor saturates when output values of the sensors are not within predetermined upper and lower bounds set by the sensor configurations of the filter. If either sensor saturates, IMU sensor subdetector **440** triggers a fault. The estimator update quality subdetector **450** looks at different statistics in the filter to determine whether or not the filter is running properly. If the filter is not running properly, Estimator Update Quality Subdetector **450** issues a fault.

[0035] The illustration of fault detector **410** in FIG. **4** is not meant to imply physical or architectural limitations to the manner in which different advantageous embodiments may be implemented. Other components in addition and/or in place of the ones illustrated may be used. Some components may be unnecessary in some advantageous embodiments. Also, the blocks are presented to illustrate some functional components. One or more of these blocks may be combined and/or divided into different blocks when implemented in different advantageous embodiments. For example, IMU sensor data subdetector **440** and Visual Sensor data subdetector **430** may be represented as a single functional block.

[0036] Turning now to FIG. **5**, a flowchart of a method **500** of fault detection in accordance with an illustrative embodiment of the disclosure is illustrated. Fault detection system **300** as illustrated in FIG. **3** begins operation of the fault detector **350** at **510** in FIG. **5**. System **300** continually generates sensor data and filter statistics for input to the fault detector **350** at **520**. Sensor data may comprise IMU data **320**, feature tracks **310** and data from an accelerometer and a gyroscope. At **530**, the fault detector **350** starts timestamp checking for each of its subdetectors to keep track of time. The subdetectors of the fault detector are activated at **540**. If an error condition exists in any subdetector for a predetermined period of time after the subdetectors are activated at **540**, then a fault signal **370** is activated from the fault detector **350**. Timestamp checking keeps track of a predetermined period of time that may be initially set by a filter configuration routine. At **550**, timestamp checking is ended. At **560**, the system **300** ends fault detection.

[0037] In FIG. **6**, a flowchart **600** of a method of operation of the loose-coupled subdetector in the system of FIG. **4** in accordance with an illustrative embodiment of the disclosure is disclosed. The loose coupled subdetector may be activated by the system at **610**. At **620**, the loose coupled subdetector inputs system sensor data and filter data. However, operation of the loose coupled subdetector continues based on whether or not motion is detected. Motion may be detected when one or more system cameras are moving to keep track of a feature. At **625**, the loose coupled subdetector determines whether the velocity of the camera motion is greater than a predetermined value. The predetermined value may be preset by a filter configuration routine. In an embodiment, the predetermined value may be greater than 0.5 meters per second. The operation of the loose coupled subdetector continues if the velocity condition is satisfied. Otherwise, the operation of the loose coupled subdetector ends at **630**. In a continuing operation of the loose coupled subdetector, a translation vector is obtained from the RANSAC algorithm at **640**. In some embodiments, RANSAC may be running in the background of processor operations. At **650**, the loose coupled subdetector may choose one or more system cameras from which to extract inliers. Inliers are feature tracks that are consistent with RANSAC's estimated camera motion. At **660**, the ratio of inliers to the total number of features in the camera images are determined. If it is determined at **665** that the ratio of inliers to the total number of features is not low, the loose coupled subdetector may end processing at **670**. If it is determined at **665** that the ratio of inliers to the total number of features is low, then a translation angle between the filter and the results of RANSAC is checked. If the difference in the translation angle between the RANSAC computed vector and the filter computed vector is around 25 degrees or less, then the angle difference is considered to be low or good. If it is determined that the angle is good at **685**, then the loose coupled subdetector ends at **690**. At **685**, if it is determined that the angle is not good, then at **695**, the loose coupled subdetector issues a fault.

[0038] Turning now to FIG. **7**, a flowchart **700** of a method of operation of the visual sensor data subdetector of the system of FIG. **4** in accordance with an illustrative embodiment of the disclosure is illustrated. The visual sensor data subdetector begins at **710** and sensor data and filter data are input at **720**. The visual sensor data subdetector conducts a minimum velocity check at **730** to determine whether image sensors, such as cameras, are stationary or moving. If, based on the minimum velocity check at **730**, the camera is stationary or is moving at a speed that is less than a predetermined value, the subdetector continues operation at **740**. Otherwise the visual sensor data subdetector ends operation at **735**. At **740**, the Visual Sensor subdetector determines a number of RANSAC inliers and the ratio of RANSAC inliers for all the observed features. A check is done at **750** to determine whether the number and ratio is below predefined values. If the number and ratio are not below predefined values, a fault is issued at **760**. If the number and ratio is below predefined values, the visual sensor check subdetector ends at **770**.

[0039] In FIG. **8**, a method of the IMU sensor data subdetector in the fault detector of FIG. **4** in accordance with an illustrative embodiment of the disclosure is illustrated. In flowchart **800**, the IMU sensor data subdetector **440** begins operation at **810**. The IMU sensor data subdetector **440** may contain internal sensors such as an accelerometer sensor and a gyroscope sensor. At **820**, the IMU sensor data subdetector **440** inputs data from the accelerometer and the gyroscope of the IMU. The accelerometer and the gyroscope sensors are checked at **830** to determine whether or not one the sensors are saturated. In determining whether or not a sensor may be saturated, the values of the inputs are compared with programmable predetermined values of an upper and lower bound. If the input values do not satisfy the values of the upper and lower bound, the IMU sensor data subdetector **440** issues a fault at **850**. The upper and lower bounds may be variable and are predetermined in the system. If the input values satisfy the values of the upper and lower bound, the operation ends at **840**.

[0040] Turning now to FIG. **9**, flowchart **900** illustrates the method of operation of the estimator update quality subdetector in the fault detector of FIG. **4** in accordance with an illustrative embodiment of the disclosure. The estimator update quality subdetector **450** of FIG. **4** reviews filter statistics output from the filter to determine whether the filter is running properly and able to provide stable 6DoF pose estimates.

[0041] The method of estimator update quality subdetector **450** begins operation at **910** with the input of sensor data and filter statistics at **920**. At **925**, the estimator update quality subdetector **450** checks whether a filter update has failed. If a filter update has failed, at **930**, the estimator update quality subdetector **450** sends a fault. If the filter update has not failed, at **935** the estimator update quality subdetector **450** checks whether the gyroscope has a fast rotation. If the gyroscope has a fast rotation then the estimator update quality subdetector **450** ends at **940**. If the gyroscope does not have a fast rotation, a comparison between the number and ratio of inliers is done at **950**. At **955**, the estimator update quality subdetector **450** checks whether the number of inliers or the ratio of inliers to the total number of features are larger than a predefined value. If the number of inliers or the ration of inliers to the total number of features is not good, the estimator update quality subdetector **450** sends a fault at **960**. If the number of inliers or the ratio of inliers to the total number of features is good, the estimator update quality subdetector **450** ends operation at **965**.

[0042] FIG. **10** illustrates a block diagram of a processing system in which a fault detection system may be implemented in accordance with an illustrative embodiment of the disclosure. In FIG. **10**, processing system **1000** includes the display device **108**, the imaging sensors **114**, **116**, and the depth sensor **120**. Processing system **1000** further includes a sensor hub **1002**, one or more processors **1004** (e.g., a CPU, GPU, or combination thereof), a display controller **1006**, a system memory **1008**, a set **1010** of non-image sensors, and a user interface **1012**. The user interface **1012** includes one or more components manipulated by a user to provide user input to the HMD **100**, such as a touchscreen, a mouse, a keyboard, a microphone, various buttons or switches, and various haptic actuators. The set **1010** of non-image sensors can include any of a variety of sensors used to provide non-image context or state of the HMD **100**. Examples of such sensors include a gyroscope **1020**, a magnetometer **1022**, an accelerometer **1024**, and an ambient light sensor **1026**. The non-image sensors further can include various wireless reception or transmission based sensors, such as a GPS receiver **1028**, a wireless local area network (WLAN) interface **1030**, a cellular interface **1032**, a peer-to-peer (P2P) wireless interface **1034**, and a near field communications (NFC) interface **1036**.

[0043] HMD **100** of FIG. **1** further has access to various datastores **1042** storing information or metadata used in conjunction with its image processing, location mapping, and location-utilization processes. The datastores **1042** can include a spatial feature datastore to store metadata for 2D or 3D spatial features identified from imagery captured by the imaging sensors of the HMD **100**, a SLAM datastore that stores SLAM-based information, such as mapping information for areas of the local environment **112**, as illustrated in FIG. **2**, already explored by the HMD **100**, an AR datastore that stores AR overlay information or VR information, such as CAD-based representations of the relative locations of objects of interest in the local environment **112**. The datastores **1042** may be local to the HMD **100**, such as on a hard drive, solid state memory, or removable storage medium (not shown), the datastores **1042** may be remotely located at one or more servers and accessible via, for example, one or more of the wireless interfaces of the HMD **100**, or the datastores **1042** may be implemented as a combination of local and remote data storage.

[0044] In operation, the imaging sensors **114**, **116** capture imagery of a local environment, the sensor hub **1002** processes the captured imagery to produce modified imagery, and the display controller **1006** controls the display device **108** to display the modified imagery at the display device **108**. Concurrently, the processor **1004** executes one or more software programs **1040** to provide various functionality in combination with the captured imagery, such spatial feature detection processes to detect spatial features in the captured imagery or in depth information captured by the depth sensor **120**, the detection of the current pose of the HMD **100** based on the detected spatial features or the non-sensor information provided by the set **1010** of non-image sensors, the generation of AR overlays to be displayed in conjunction with the captured imagery, VR content to be displayed in addition to, or as a representation of the captured imagery, and the like. For example, the fault detector **410** as illustrated in FIG. **4** may be part of the software programs **1040** that are executed by the processor.

[0045] In some embodiments, certain aspects of the techniques described above may implemented by one or more processors of a processing system executing software. The software comprises one or more sets of executable instructions stored or otherwise tangibly embodied on a non-transitory computer readable storage medium. The software can include the instructions and certain data that, when executed by the one or more processors, manipulate the one or more processors to perform one or more aspects of the techniques described above. The non-transitory computer readable storage medium can include, for example, a magnetic or optical disk storage device, solid state storage devices such as Flash memory, a cache, random access memory (RAM) or other non-volatile memory device or devices, and the like. The executable instructions stored on the non-transitory computer readable storage medium may be in source code, assembly language code, object code, or other instruction format that is interpreted or otherwise executable by one or more processors.

[0046] A computer readable storage medium may include any storage medium, or combination of storage media, accessible by a computer system during use to provide instructions and/or data to the computer system. Such storage media can include, but is not limited to, optical media (e.g., compact disc (CD), digital versatile disc (DVD), Blu-Ray disc), magnetic media (e.g., floppy disc, magnetic tape, or magnetic hard drive), volatile memory (e.g., random access memory (RAM) or cache), non-volatile memory (e.g., read-only memory (ROM) or Flash memory), or microelectromechanical systems (MEMS)-based storage media. The computer readable storage medium may be embedded in the computing system (e.g., system RAM or ROM), fixedly attached to the computing system (e.g., a magnetic hard drive), removably attached to the computing system (e.g., an optical disc or Universal Serial Bus (USB)-based Flash memory), or coupled to the computer system via a wired or wireless network (e.g., network accessible storage (NAS)).

[0047] Note that not all of the activities or elements described above in the general description are required, that a portion of a specific activity or device may not be required, and that one or more further activities may be performed, or elements included, in addition to those described. Still further, the order in which activities are listed are not necessarily the order in which they are performed. Also, the concepts have been described with reference to specific embodiments. However, one of ordinary skill in the art appreciates that various modifications and changes can be made without departing from the scope of the present disclosure as set forth in the claims below. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope of the present disclosure.

[0048] The various embodiments of the present disclosure illustrate the implementation of a fault detection system that enables quick error detection and recovery to enable a more stable motion tracking. The system includes at least four subdetector modules that are running simultaneously. When any one of the four subdetectors in the system detects an error, a fault is triggered in the system. The system may then quickly recover and reinitialize for continued motion tracking.

[0049] Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any feature(s) that may cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature of any or all the claims. Moreover, the particular embodiments disclosed above are illustrative only, as the disclosed subject matter may be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. No limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above may be altered or modified and all such variations are considered within the scope of the disclosed subject matter. Accordingly, the protection sought herein is as set forth in the claims below.

What is claimed is:

1. A method of fault detection in motion tracking, comprising:

receiving sensor data and filter statistics to a fault detector;

identifying a failure in at least one of a plurality of subdetectors of the fault detector based on the sensor data and filter statistics; and

providing a fault signal from the fault detector to a filter in response to the failure identification.

2. The method of claim **1**, further comprising:

initiating timestamp tracking; and

identifying the failure in response to a condition in at least one of the plurality of subdetectors that exists for a predetermined period of time, the predetermined period of time being set by a filter configuration routine.

3. The method of claim **1**, where the sensor data and filter statistics comprise inertial measurement unit (IMU) data and feature tracks.

4. The method of claim **1**, further comprising:

activating a subdetector of the plurality of subdetectors.

5. The method of claim **4**, wherein activating the subdetector comprises activating a loose-coupled subdetector in response to an image sensor velocity being greater that a threshold velocity.

6. The method of claim **5**, wherein the loose coupled subdetector identifies a failure in response to an angle of translation of a vector of an image from a filter and an output from RANSAC not being within a threshold limit.

7. The method of claim **4**, wherein activating the subdetector comprises activating a visual sensor data subdetector in response to an image sensor velocity being greater that a threshold velocity.

8. The method of claim **7**, wherein the visual sensor data subdetector determines a number of RANSAC inliers and a ratio of RANSAC inliers to all observed features.

9. The method of claim **8**, wherein the visual sensor data subdetector determines a failure in response to the number and the ratio being below a predetermined threshold.

10. The method of claim **4**, wherein activating the subdetector comprises activating an inertial measurement unit (IMU) sensor data subdetector based on the sensor data from an accelerometer and a gyroscope.

11. The method of claim **10**, wherein the IMU sensor data subdetector determines a failure in response to signals being measured by the accelerometer and gyroscope being larger that a dynamic range associated with the accelerometer and gyroscope.

12. The method of claim **4**, wherein activating the subdetector comprises activating an estimator update quality subdetector to determine whether the filter is performing motion tracking accurately.

13. The method of claim **12**, wherein the estimator update quality subdetector identifies a failure in response to determining that a number of inliers to a ratio of inliers to a total number of features is not within a predetermined estimate.

14. A system for performing fault detection in motion tracking, comprising:

a filter;

a fault detector associated with the visual inertial odometry filter; and

a feature processing block associated with the visual-inertial-odometry filter and the fault detector.

15. The system of claim **14**, wherein the fault detector comprises at least four subdetectors.

16. The system of claim **15**, wherein the at least four subdetectors include a loose-coupled subdetector, an inertial measurement unit (IMU) sensor data subdetector, a visual sensor data subdetector, and an estimator update quality subdetector.

17. The system of claim **15**, wherein the fault detector outputs a fault in response to the at least one of the four subdetectors outputting a fault.

18. The system of claim **14**, wherein the filter is a visual inertial odometry filter.

19. A non-transitory computer readable medium having stored therein instructions, which when executed by a processor, perform a method comprising:

receiving sensor data and filter statistics to a fault detector;

identifying a failure in at least one of a plurality of subdetectors of the fault detector based on the sensor data and filter statistics; and

outputting a fault signal from the fault detector to a filter in response to the failure identification.

20. The non-transitory computer readable medium of claim **19**, the method further comprising:

initiating timestamp tracking; and

identifying the failure in response to a condition in at least one of the plurality of subdetectors that exists for a predetermined period of time, the predetermined period of time being set by a filter configuration routine.

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