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(54) **CONTROL SYSTEM FOR A WEAPON MOUNT**

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(51) **Int. Cl.**
F41A 19/36 (2006.01)

(52) **U.S. Cl.** **89/136**

(58) **Field of Classification Search** 89/136
See application file for complete search history.

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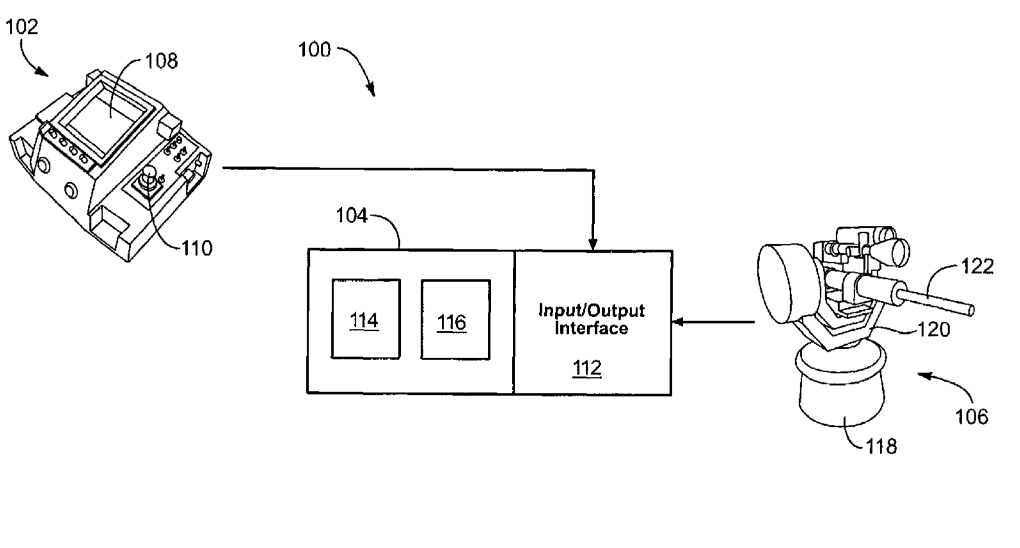
(57) **ABSTRACT**

A control system stabilizes a turret having a gimbal and base and pointing a weapon mounted within the turret. The control system includes computer executable modules to receive turret data and operator commands and to modify operator commands in accordance with a generated line of sight vector and ballistic data. The modules include a time optimal controller to generate modified operator commands. The modules further include a gimbal stabilization controller to generate motor commands to stabilize the turret and point the weapon.

9 Claims, 6 Drawing Sheets



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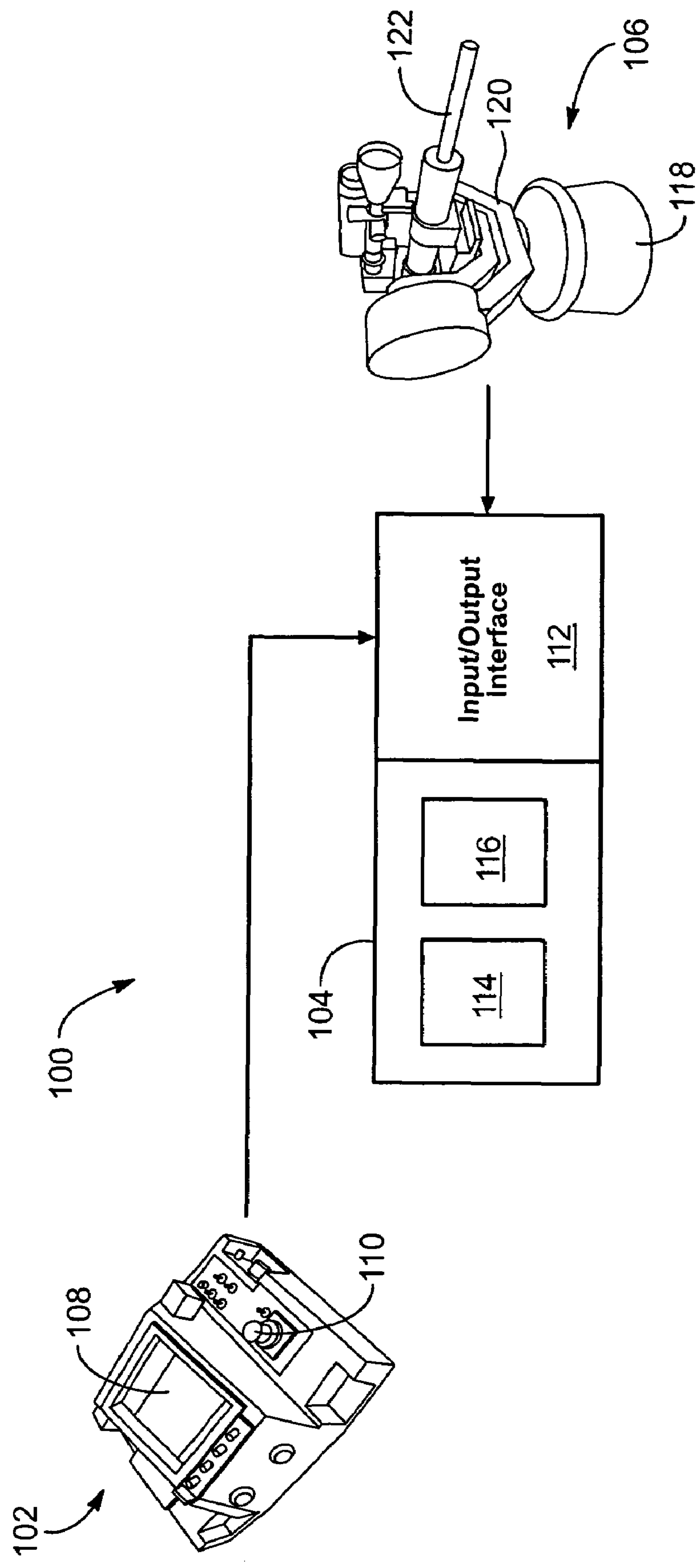

122
106
120
118
Input/Output Interface
112
116
114
104
100
108
110
102

FIG. 1

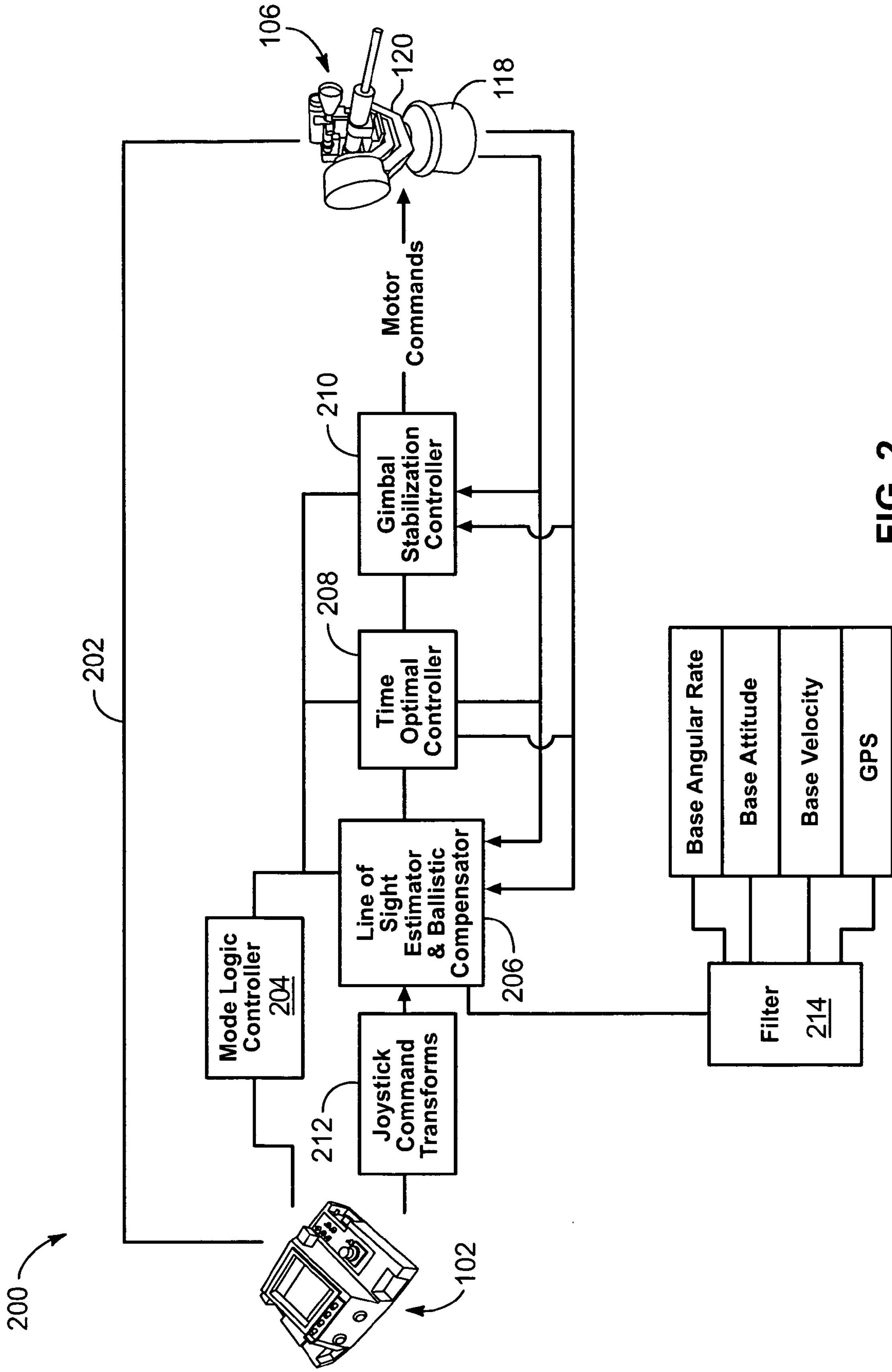
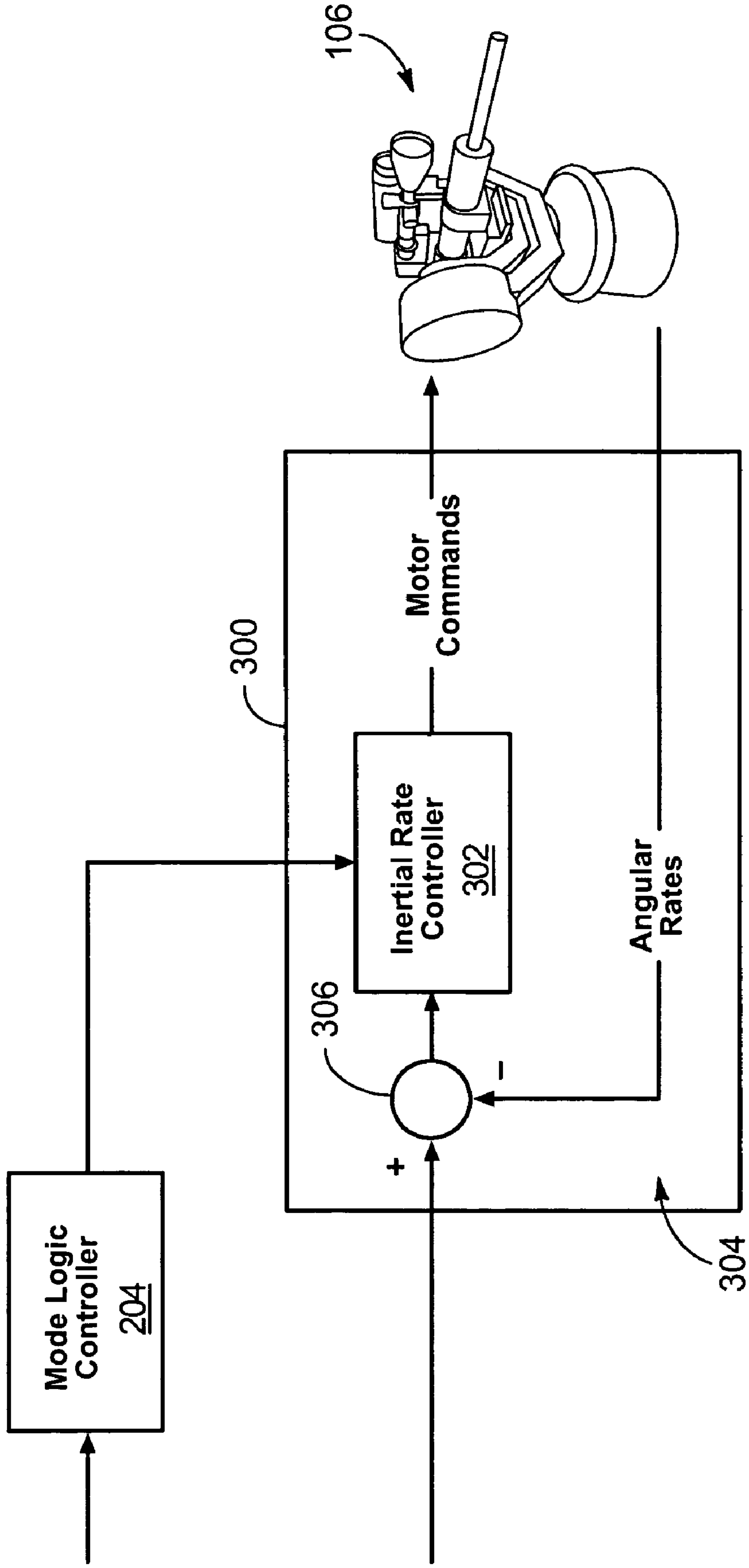

200
202
106
120
118
Motor Commands
210
Gimbal Stabilization Controller
208
Time Optimal Controller
Line of Sight Estimator & Ballistic Compensator
206
Mode Logic Controller 204
Joystick Command Transforms
212
102
Base Angular Rate
Base Attitude
Base Velocity
GPS
Filter 214

FIG. 2



106
Motor Commands
300
Inertial Rate Controller
302
306
Angular Rates
Mode Logic Controller
204
+
-
304

FIG. 3

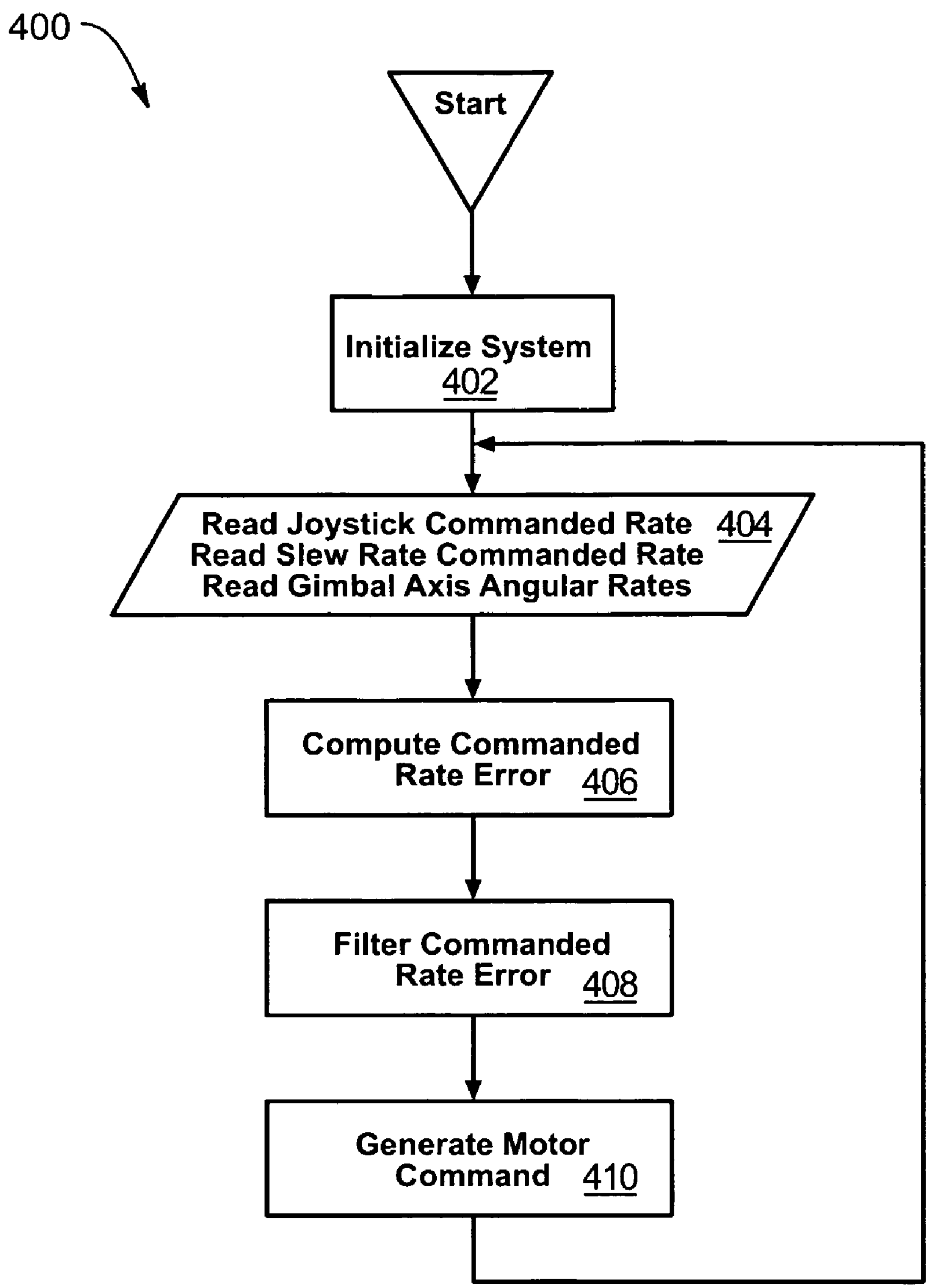

400
Start
Initialize System 402
Read Joystick Commanded Rate 404
Read Slew Rate Commanded Rate
Read Gimbal Axis Angular Rates
Compute Commanded Rate Error 406
Filter Commanded Rate Error 408
Generate Motor Command 410

FIG. 4

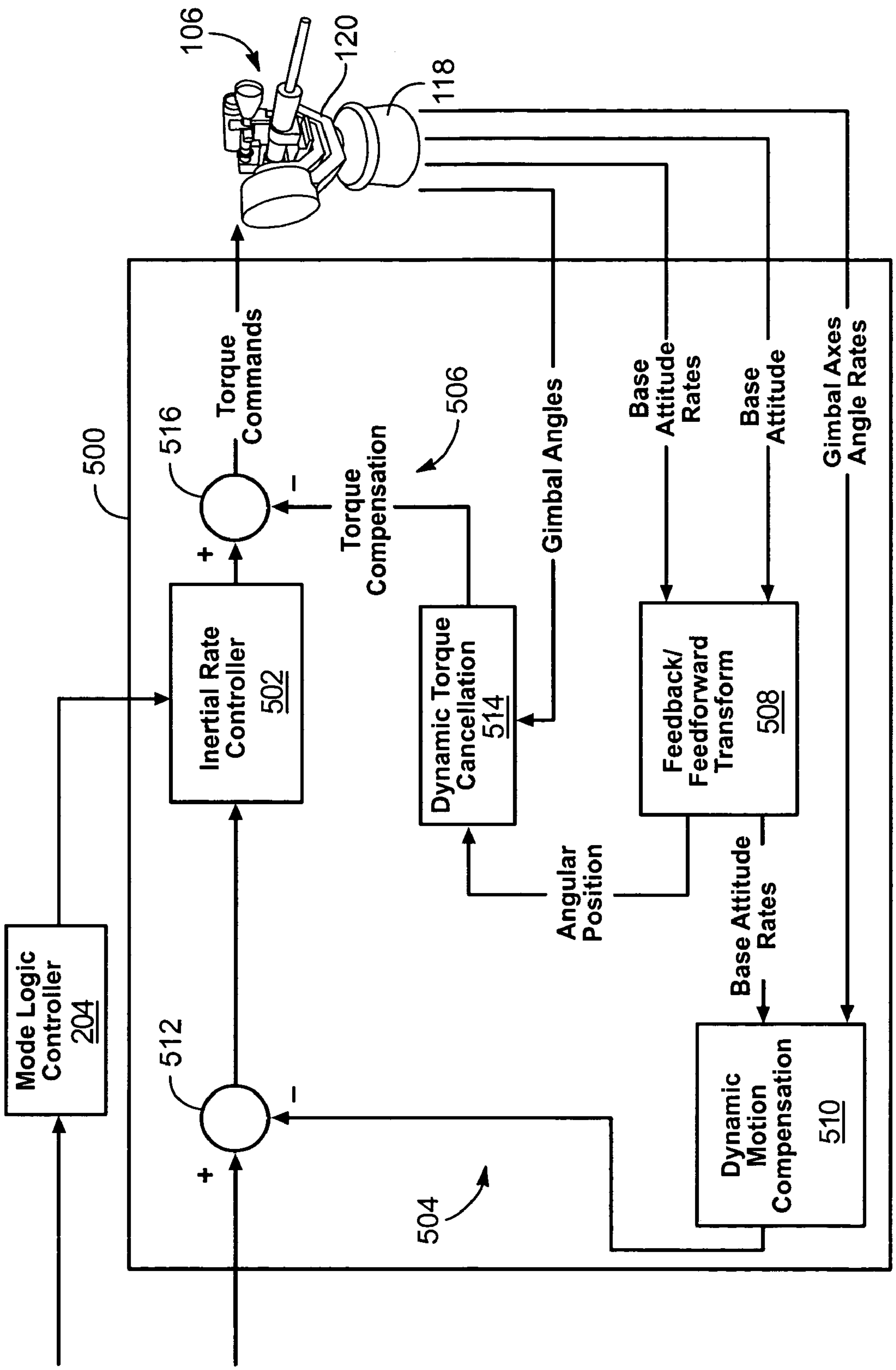

106
120
118
500
516
Torque Commands
506
Torque Compensation
Gimbal Angles
Base Attitude Rates
Base Attitude
Gimbal Axes Angle Rates
Inertial Rate Controller
502
Dynamic Torque Cancellation
514
Feedback/ Feedforward Transform
508
Angular Position
Base Attitude Rates
Mode Logic Controller
204
512
Dynamic Motion Compensation
510
504
+
-
+
-

FIG. 5

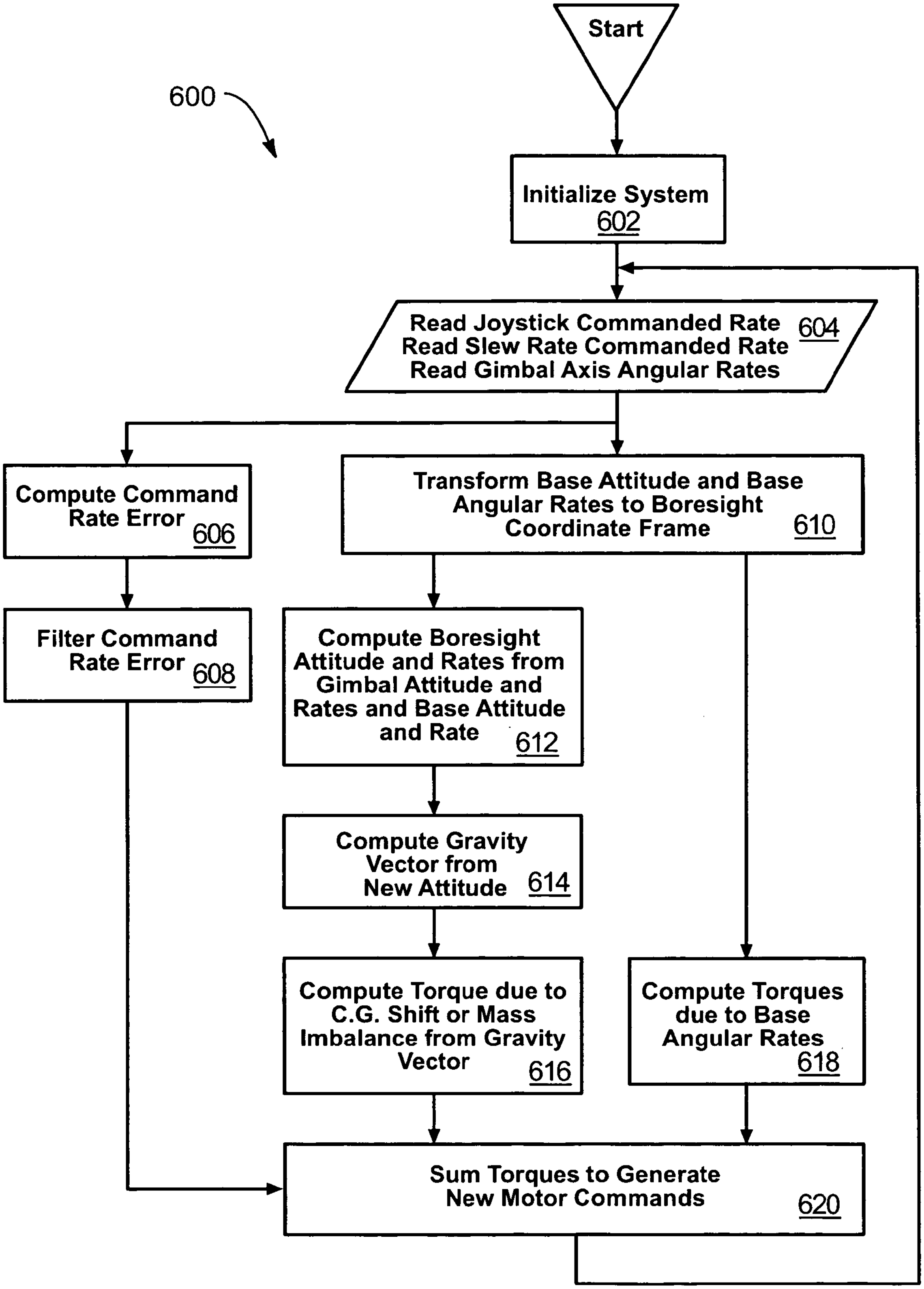

600
Start
Initialize System 602
Read Joystick Commanded Rate
Read Slew Rate Commanded Rate
Read Gimbal Axis Angular Rates 604
Compute Command Rate Error 606
Transform Base Attitude and Base Angular Rates to Boresight Coordinate Frame 610
Filter Command Rate Error 608
Compute Boresight Attitude and Rates from Gimbal Attitude and Rates and Base Attitude and Rate 612
Compute Gravity Vector from New Attitude 614
Compute Torque due to C.G. Shift or Mass Imbalance from Gravity Vector 616
Compute Torques due to Base Angular Rates 618
Sum Torques to Generate New Motor Commands 620

FIG. 6

CONTROL SYSTEM FOR A WEAPON MOUNT

RELATED APPLICATIONS

This application claims priority to U.S. Patent Application No. 60/538,280 filed on Jan. 20, 2004 and entitled "Control System for Remotely Operated Weapon Turrets."

TECHNICAL FIELD

The present invention relates to systems for a stabilizing a weapon mount and for pointing a weapon supported within the weapon mount.

BRIEF DESCRIPTION OF THE DRAWINGS

A more particular description of the invention briefly described above will be rendered by reference to the appended drawings. Understanding that these drawings only provide information concerning typical embodiments of the invention and are not therefore to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIG. **1** is a block diagram of one embodiment of a weapon system.

FIG. **2** is a block diagram of one embodiment of a control system for use with the weapon system of FIG. **1**.

FIG. **3** is a block diagram of a gimbal stabilization controller.

FIG. **4** is a flow diagram of a process performed in accordance with the gimbal stabilization controller of FIG. **3**.

FIG. **5** is a block diagram of an embodiment of a gimbal stabilization controller in accordance with the present invention; and

FIG. **6** is a flow diagram of a process performed in accordance with the gimbal stabilization controller of FIG. **5**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The presently preferred embodiments of the present invention will be best understood by reference to the drawings, wherein like parts are designated by like numerals throughout. It will be readily understood that the components of the present invention, as generally described and illustrated in the figures herein, could be arranged and designed in a wide variety of different configurations. Thus, the following more detailed description of the embodiments of the apparatus, system, and method of the present invention, as represented in FIGS. **1** through **6**, is not intended to limit the scope of the invention, as claimed, but is merely representative of presently preferred embodiments of the invention.

The present invention provides a weapon control system to stabilize a base and gimbal assembly and point a mounted weapon. The control system includes various cascaded control loops that provide stabilization, pointing control, and ballistics compensation so that the mount can be operated by either a human operator or a tracking system. The architecture of the control system is such that communications between the operator's console can be connected through either a wire umbilical or a wireless link.

Referring to FIG. **1**, a weapon system **100** is shown which includes an operator console **102**, a computer **104**, and a weapon turret **106** which are all in electrical communication with one another. The weapon system **100** may be produced with a size and weight that is manually portable without a vehicle.

The operator console **102** may be embodied in a variety of ways and includes a housing that may be formed by blow molded plastic or metal. The operator console **102** may be sized to fit in ergonomically in a lap or may be configured to fit within an instrument panel of a vehicle. The operator console **102** includes input devices, such as switches, potentiometers, buttons, and the like, to receive operator commands relating to mode, positioning, and firing. The operator console **102** may further include a display **108** to provide a visual as viewed by a scope or camera mounted to the turret **106**. The operator console **102** may include other input devices such as a joystick **110** or similar device to control movement of the turret **106**. Additional input devices may provide overall system power control, mode control, servo amplification, and trigger control. The based on operator input, the operator console **102** generates operator commands that includes mode, slew, slew rate selector, joystick movement, and trigger. Operator commands are delivered to the computer **104** through hard wire or wireless connection.

The computer **104** includes a input/output interface **112** for data acquisition capabilities and to provide output to both the operator console **102** and to the turret **106**. The computer **104** further includes a processor **114** for executing computer readable instructions and a memory **116** for storing one or more computer executable modules and data. Although modules may be implemented in software, one of skill in the art will appreciate that the modules may also be implemented in analog hardware or in a combination of software and hardware. Both processor **114** and memory **116** may be implemented using any one of a variety of commercially available components.

The weapon turret **106** may be sized and configured to receive and support a variety of different caliber weapons, including a .50 caliber weapon with a muzzle brake or a non-lethal weapon. The weapon turret **106** may be mounted on manned or unmanned aircraft, watercraft, and land vehicles. The weapon turret **106** can also be emplaced in fixed emplacements such as runway thresholds, bunkers, sentry points, military perimeters, outposts, or other field settings.

The turret **106** includes a base **118** that supports a two-axes gimbal **120**. The two-axes gimbal **120** may include DC torque motors to provide movement in each axis and to support a weapon **122**. The turret **106** includes angular rate sensors to measure the angle rate of each gimbal axis. An angular rate sensor may be embodied as a magneto-hydrodynamic angular rate sensor. An angular rate sensor may also be embodied as one or more rate gyros. The turret **106** may include position sensors, such as rotary potentiometers, resolvers, or encoders, to measure the gimbal axes angles. In application, resolvers are more robust and have superior resolution than other sensors, but an optical encoder may also be used. The turret **106** may include a GPS or variant of a GPS such as GLONASS, Galileo, WMS, DGPS, etc. to measure the geographic position.

The turret **106** may include orthogonally mounted angular rate sensors to measure the base angular rate in 3 degrees of freedom. The turret **106** includes attitude sensors, such as tilt sensors (inclinometers) or magnetic field sensors (magnetometers) to measure the base attitude and the base attitude rate. The turret **106** may further include one or more accelerometers to measure the base velocity. The base angular rate and base attitude can be combined and filtered using a complementary filter or an extended Kalman filter to generate a six degree of freedom model of positions and/or velocities of the base to be used in ballistic compensation, stabilization and pointing.

As can be appreciated, turret sensors may vary in their design, implementation, and placement. All such devices that measure gimbal axes angles, gimbal axes angle rates, base attitude, base attitude rates, base angular rate, base velocity, and GPS may be incorporated into a turret of the present invention. As referred to herein turret data includes all information measured by a sensor included within a turret **106**.

Referring to FIG. **2**, a control system **200** is shown and includes modules that are used to operate the weapon system **100**. The control system **200** may be implemented in software stored within the memory **116**, analog hardware, or by other forms of controls such as state-space controls, or a combination thereof. The control system **200** includes a combination of cascaded control loops for gimbal stabilization, weapon pointing, and ballistics compensation. The control system **200** further provides a communication **202** between the operator console **102** and the turret **106** to transmit a trigger command to fire a weapon.

The control system **200** includes a mode logic controller **204** to configure the components of the system **200** for a selected mode. The mode logic controller **204** receives a mode command from the operator console **102** to indicate a selected mode. The modes of operation may include home, velocity, position, and tracking. The home mode moves the gimbal **120** back to a home position and retains the gimbal **120** in the home position. The velocity mode configures the system **200** to follow commanded velocity inputs. The position mode configures the system **200** to point and hold a desired position. The desired position may be determined by a certain angle or position coordinate. The tracking mode configures the system for following targets where the coordinates are predetermined either through a tracking system or target designator.

The mode logic controller **204** is in communication with a line of sight (LOS) estimator and ballistic compensator **206**, a time optimal controller **208**, and a gimbal stabilization controller **210** to effect their operation in accordance with a mode. In the home and velocity modes, only the gimbal stabilization controller **210** operates to direct the gimbal's rate and position. In the position and tracking modes, the LOS estimate and ballistic compensator **206**, time optimal controller **208**, and gimbal stabilization controller **210** all operate to stabilize and obtain position. In the tracking mode, the joystick **110** is disabled as a tracking system (not shown) replaces joystick commands. In the position mode, the joystick **110** is enabled and generates commands to obtain position.

The control system **200** includes a joystick command transform module **212** to receive joystick commands and transform the commands into the same frame of reference as the gimbal axes. The joystick command transform module **212** delivers the joystick commands to the LOS estimator and ballistics compensator **206**. The turret **106** transmits sensor data indicative of gimbal axes angular rates, gimbal axes angle, base attitude rate, and base attitude.

The control system **200** further includes a filter **214** that receives sensor data from the turret **106** indicative of base angular rate, base attitude, base velocity, and GPS. The filter **214** generates a model of positions and/or velocities of the base **118**. The filter **214** sends the model to the LOS estimator and ballistics compensator **206** which is used in ballistic compensation, stabilization, and pointing.

The LOS estimator and ballistics compensator **206** computes the trajectory movements needed to point at a target. The LOS estimator and ballistics compensator **206** actively computes the difference in boresight of the weapon (pitch and yaw axis) and the base's position and attitude in 3 space. The LOS estimator and ballistics compensator **206** further computes the offset due to the ballistics of a current round due to turret and mount dynamics that include linear and angular rate velocity, target range, winds, altitude and temperature.

The LOS estimator and ballistics compensator **206** computes a vector from the barrel boresight to the target. If the target coordinates are known, the LOS estimator and ballistics compensator **206** generates a vector to the target for a pointing command. To compute the LOS, the gimbal axes angles, gimbal axes angular rates, base position, base velocity, base attitude, and base angular rate are used. The LOS estimator and ballistic compensator **206** generates a vector that points from the origin of a gimbal boresight frame of reference to the origin of the target's frame of reference. The target coordinate may come from operator entered coordinates from a target recognition and tracking system.

If the target coordinates are unknown, but the target can be seen, then the distance to the target is determined. The distance to the target can be determined from a distance measuring device such as a laser rangefinder or inputted from operator estimate. The LOS is computed from the gimbal axes angles, gimbal axes angular rates, base position, base velocity, base angular rate, and base attitude. Once the LOS estimator and ballistic compensator **206** computes a vector, the distance data can be applied to determine the coordinates of the target. Once the coordinates of the target are known, standard techniques to compute the ballistic trajectory of bullet are used.

The LOS estimator and ballistic compensator **206** delivers commands to the time optimal controller **208**. The time optimal controller **208** allows the LOS or position to move rapidly for large angle changes and slowly for small changes. The time optimal controller **208** may include a Luenberger compensator adapted for use with gimbals. The time optimal controller **208** can limit gimbal rates and acceleration, deal with non-linear large angle movements and linear small angle movements. The time optimal controller **208** assists with pointing by splitting movements into large angle and small angle movements. By splitting the type of movement, overshoot and pointing offset can be addressed. The time optimal controller **208** delivers commands to the gimbal stabilization controller **210** that generates motor commands to the turret **106**.

Referring to FIG. **3**, a gimbal stabilization controller **300** is shown. The gimbal stabilization controller **300** includes an inertial rate controller **302** that operates in conjunction with a stabilization loop **304**. The intertial rate controller **302** may be implemented in various ways depending on the rate sensors used and the type of performance required by the system **200**. The stabilization loop **304** provides outputs to the turret **106** and receives position feedback from the turret **106**. The stabilization loop **304** and inertial rate controller **302** operate together to ensure that the gimbal **120** moves at the commanded rate and to compensate for torque disturbances due to weapon recoil, base movement, gravity, and coriolis effect.

The inertial rate controller **302** receives mode, operator commands, gimbal axes angels, gimbal axes angle rates, base attitude, and base attitude rates. The intertial rate controller **302** allows the turret **106** to move at commanded rates, but it is unable to compensate for base motion or other disturbances. The stabilization loop **304** provides a reasonable basis for most disturbance rejection such as recoil. In operation, the angular rate for each gimbal axis is received by the gimbal stabilization controller **300** and subtracted **306** from a commanded angular rate to generate an error signal. The error signal is transmitted to the inertial rate controller **302** which filters the error signal. Based on the error signal, the inertial rate controller **302** transmits torque commands to the turret **106**.

Referring to FIG. **4**, a flow diagram of a method **400** performed in conjunction with the gimbal stabilization controller **300** of FIG. **3** is shown. The control system **200** commences operation by initializing **402** the system **200**. The system gimbal stabilization controller **300** receives and reads **404** the joystick commanded rate, slew rate, and gimbal axes angular rates. The gimbal stabilization controller **300** computes **406** an error signal based on the difference between the measured gimbal axes angular rates and the commanded gimbal axes angular rates. The error signal is filtered **408** by the inertial rate controller **302**. The inertial rate controller **302** then generates **410** motor commands to the turret **106** to control stabilization and pointing.

Referring to FIG. **5**, an alternative embodiment of a gimbal stabilization controller **500** is shown. The gimbal stabilization controller **500** includes an inertial rate controller **502** that may be embodied as a second order phase lead compensator having the form of:

$$\frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)}.$$

The inertial rate controller **502** provides a constant output response over a broad frequency region. Depending on the desired performance, it may be required to chose z_1, z_2, p_1, and p_2 such that the response has a higher response at low frequencies and a lower response otherwise.

The gimbal stabilization controller **500** includes both feedback **504** and feedforward loops **506** for stabilization. The feedforward loop **504** addresses inadequacies of a inertial rate controller **502** which does not compensate for base angular rates, mass imbalances, or off-axis centers of gravity of the weapon system being used.

The gimbal stabilization controller **500** includes a feedback/feedforward transform module **508** that receives the base attitude and base attitude rate from the turret **106**. The feedback/feedforward module **508** applies a series of spatial transformations so that the base attitude and base attitude rate are in the same frame of reference as the gimbal axes which ideally are co-planar with a weapon boresight. The frame of reference may be an earth centered inertial coordinate frame. Once all measurements are in the same frame of reference, torque and angular rate errors can be computed. Torque errors may be attributed to factors such as friction, gravity, coriolis effect, etc. The most common torque error is attributed to the center of gravity of the turret **106** not being at the intersection of the gimbal axes and weapon boresight. This misalignment generates off-axis torques that are a function of the gravity vector. The gravity vector is a function of the transformed base attitude angles and gimbal angles. Generally simple vector addition yields the gravity vector but it may not be the case for all situations, especially those where artificial gravity environments can exist due to base motion accelerations. The most desirable error is where center of gravity is located below an axis with respect to gravity. In this example, torque compensation is the common pendulum function.

The feedback/feedforward transform module **508** delivers base attitude rates to a dynamic motion compensation module **510**. The dynamic motion compensation module **510** computes the gimbal angular rate by subtracting the base angular rate from the gimbal axes angular rate. This allows command rates to be achieved on a moving platform. The gimbal angular rate is then subtracted **512** from the command angular rate to generate an error signal. The inertial rate controller **502** receives the error signal, filters the error signal, and generates a proportional torque or motor command.

The feedforward loop **506** includes a dynamic torque cancellation module **514** that receives base angular position and gimbal axes angels. The dynamic torque cancellation module **514** generates torque compensation to offset effects on the base **116** such as base angular rates, mass imbalances, and off-axis centers of gravity of the weapon system being used. The generated torque compensation is summed with the proportional torque command to generate a final torque command that is transmitted to the turret **106**.

Referring to FIG. **6**, a method **600** performed in accordance with a control system **200** having a gimbal stabilization controller **500** of FIG. **5** is shown. The method **600** begins by initializing **602** the control system **200**. The operator commands, such as joystick commanded rate and slew rate commanded rate, as well as the gimbal axes angular rates are read **604**. The gimbal stabilization controller **500** computes **606** an error signal based on the difference between the measured gimbal axes angular rates and the commanded gimbal axes angular rates. The error signal is filtered **608** by the inertial rate controller **502**. The feedback/feedforward transform module transforms **610** the base attitude and base angular rates to the gimbal frame of reference, such as a boresight coordinate frame of reference.

The dynamic torque cancellation module **514** computes **612** boresight attitude and boresight rate from gimbal attitude, gimbal attitude rate, base attitude, and base attitude rate. The dynamic torque cancellation module **514** then computes **614** a gravity vector from the boresight attitude. The dynamic torque cancellation module **514** further computes **616** torque due to center of gravity shit or mass imbalance from a gravity vector. In parallel, the dynamic torque cancellation module **514** computes **618** torques due to base angular rates. The result of steps **612**, **614**, **616**, and **618** is to generate a torque compensation which includes effects on the base **118**. The torque compensation is summed **620** to modify motor or torque commands and generate new motor commands.

The control system disclosed herein improves the accuracy of point target weapons over that of the same human operated weapon, especially in high vibration environments. Furthermore, the control system may be remotely operated thus reducing the operator's exposure. The control system may be used to stabilize and point weapons up to .50 caliber in size. In order to accurately fire a point target weapon variables such as effects on the base, gravity, velocity jump, and ballistic coefficients must be known. Conventional systems do not adequately address these issues. The gimbal stabilization controller includes feedback and feedforward loops that incorporate data from sensors to allow a weapon to be precisely pointed and ballistically compensated. These sensors include measurement of gimbal axes angles, gimbal axes angular rate sensors, base position, base attitude, base attitude rates, base angular rate, and base velocity. When sensor data is processed through a filter, an accurate velocity model, both angular and linear, is generated and used for reference in LOS targeting and ballistics compensation.

It will be obvious to those having skill in the art that many changes may be made to the details of the above-described embodiments without departing from the underlying principles of the invention. The scope of the present invention should, therefore, be determined only by the following claims.

What is claimed is:

1. A computer implemented method for stabilizing a turret having a gimbal and base and pointing a weapon mounted within the turret, comprising:

receiving operator commands including a command gimbal angular rate and turret data;

generating a line of sight vector based on the turret data;

modifying the operator commands based on the line of sight vector and ballistic data;

comparing the command gimbal angular rate to a measured gimbal angular rate to generate an error signal; and

generating torque commands based on the error signal to stabilize the turret and point the weapon.

2. The method of claim **1**, further comprising modifying operator commands into the same frame of reference as the turret.

3. The method of claim **1**, wherein the operator commands includes a selected mode and wherein modifying the operator commands, comparing the gimbal angular rate to a measured gimbal angular rate, and generating torque commands is initiated by the selected mode.

4. The method of claim **1**, further comprising filtering turret data to generate a turret position model and a turret velocity model.

5. The method of claim **4**, wherein the turret data includes base angular rate, base attitude, base velocity, and GPS data.

6. The method of claim **1**, wherein the turret data includes gimbal axes angles, gimbal axes angular rates, base attitude, and base attitude rates.

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

generating a measured gimbal angular rate based on the turret data; generating torque compensation based on the turret data; and modifying the torque commands based on the torque compensation.

8. The method of claim **7**, wherein the turret data includes base attitude rate and base attitude and further comprising modifying the base attitude rate and base attitude to be in the same frame of reference as the gimbal.

9. A computer implemented method for stabilizing a turret having a gimbal and base and pointing a weapon mounted within the turret, comprising:

receiving operator commands including a command gimbal angular rate and turret data;

generating a line of sight vector based on the turret data;

modifying the operator commands based on the line of sight vector and ballistic data;

comparing the command gimbal angular rate to a measured gimbal angular rate to generate an error signal;

generating torque commands based on the error signal to stabilize the turret and point the weapon;

generating a measured gimbal angular rate based on the turret data;

generating torque compensation based on the turret data; and

modifying the torque commands based on the torque compensation, wherein generating torque commands based on the error signal includes application of a second order phase lead compensator having the form of:

$$\frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)}.$$

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